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# Recovery potential assessment of the Gulf of St. Lawrence Designatable Unit of Winter Skate (*Leucoraja ocellata* Mitchill), January 2016

Douglas P. Swain and Hugues P. Benoît

Fisheries and Oceans Canada
Gulf Fisheries Centre
343 University Avenue,
Moncton, NB E1C 9B6

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## Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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# ABSTRACT

Winter Skate (*Leucoraja ocellata*) in the southern Gulf of St. Lawrence (sGSL) are distinct from those occurring elsewhere, maturing at a much smaller size and younger age. In 2005, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) identified Winter Skate in the sGSL as a Designatable Unit (DU) and assessed the population as Endangered. In its 2015 assessment, COSEWIC revised the DU to include the northern Gulf of St. Lawrence (nGSL). New analyses indicate that Winter Skate occur more rarely in the nGSL than previously thought and that the few confirmed specimens are of the late maturing type. Thus analyses presented here are restricted to the sGSL. Winter Skate in the sGSL have continued to decline since the 2005 assessment. Based on survey data, biomass and adult abundance have declined by 99% since the early 1980s. Once widely distributed in shallow inshore waters, their distribution is now restricted to a small area of the Northumberland Strait. There has been no directed fishery for Winter Skate in the sGSL and bycatch in other fisheries has declined to very low levels (< 5 t since 2010). Discard mortality appears to be low, about 10% in the scallop fishery and 25 to 35% in fisheries for groundfish (declining to <10% since 2007). Based on population models, fishing mortality appears to be negligible, declining from 3% annually in the early 1970s to 0.25% since 2011 for adults, and even lower for juveniles. Natural mortality is estimated to have increased to extremely high levels for adult Winter Skate, from 10% annually during 1971 to 1977 to 63% annually during 1992 to 1998, averaging 57% annually since 1999. No trend in the natural mortality of juveniles was evident, with the median estimate fluctuating around 61% annually. Increased predation by Grey Seal appears to be an important cause of the current high adult natural mortality. A Limit Reference Point (LRP) corresponding to 40% of BMSY (biomass at maximum sustainable yield) was estimated and proposed as a candidate abundance recovery target. The probability that the population was below the LRP was estimated to be 100% since 1995. Under current productivity conditions, the population is projected to continue to decline and is almost certain to be extinct by mid-century, even with no fishery removals. The recent very low levels of fishing mortality have negligible impact on the population trajectory at the current levels of the other components of productivity, in particular adult natural mortality. With no fishing, population biomass would be expected to increase slowly if adult natural mortality were decreased by 80% and relatively rapidly if decreased by 85%.

# Évaluation du potentiel de rétablissement de la raie tachetée (*Leucoraja ocellata* Mitchill) de l'unité désignable du golfe du Saint-Laurent, janvier 2016

## RÉSUMÉ

La raie tachetée (*Leucoraja ocellata*) du sud du golfe du Saint-Laurent (sGSL) diffère des autres populations de l'espèce, puisqu'elle atteint la maturité à une taille beaucoup plus petite et à un bien plus jeune âge. En 2005, le Comité sur la situation des espèces en péril au Canada (COSEPAC) a déterminé que la raie tachetée du sGSL était une unité désignable (UD) et l'a désignée comme une espèce en voie de disparition. Dans son évaluation de 2015, le COSEPAC a modifié l'UD pour y inclure le nord du golfe du Saint-Laurent (nGSL). De nouvelles analyses indiquent que la raie tachetée est plus rarement observée dans le nGSL qu'on ne le croyait, et que les quelques spécimens confirmés sont du type qui atteint la maturité plus tard. Par conséquent, les analyses présentées ici ne concernent que le sGSL. Le déclin de la population de raie tachetée du sGSL s'est poursuivi depuis l'évaluation de 2005. D'après les données des relevés, la biomasse et l'abondance des adultes ont décliné de 99 % depuis le début des années 1980. Autrefois largement répandue dans les eaux côtières peu profondes, la raie tachetée n'est aujourd'hui présente que dans une petite zone du détroit de Northumberland. Aucune pêche visant la raie tachetée n'a eu lieu dans le sGSL, et les prises accessoires dans le cadre d'autres pêches ont décliné à un niveau très faible (moins de 5 tonnes depuis 2010). La mortalité par rejet semble faible, avec environ 10 % pour la pêche au pétoncle et de 25 à 35 % pour les pêches aux poissons de fond (en baisse à moins de 10 % depuis 2007). D'après les modèles de population, la mortalité par pêche semble négligeable, passant de 3 % par année au début des années 1970 à 0,25 % depuis 2011 pour les adultes. Ce chiffre est encore plus bas pour les juvéniles. On estime que la mortalité naturelle a augmenté à des niveaux extrêmement élevés chez les raies tachetées adultes, passant de 10 % par année entre 1971 et 1977 à 63 % par année entre 1992 et 1998, avec une moyenne annuelle de 57 % depuis 1999. Aucune tendance dans la mortalité naturelle des juvéniles n'est manifeste, et l'estimation médiane fluctue autour de 61 % par année. Une augmentation de la prédation par le phoque gris semble être une cause importante de la mortalité élevée actuelle chez les adultes. Un point de référence limite correspondant à 40 % de $B_{RMS}$ (biomasse au rendement maximal soutenu) a été estimé et proposé comme objectif potentiel de rétablissement de l'abondance. La probabilité que la population soit inférieure au point de référence limite est estimée à 100 % depuis 1995. Dans les conditions actuelles de productivité, on prévoit que la population continuera de décliner et que l'espèce aura presque certainement disparu d'ici 2050, même sans prélèvements par les pêches. Les récents niveaux très faibles de mortalité par pêche ont un effet négligeable sur la trajectoire de la population au niveau actuel des autres composantes de productivité, en particulier de la mortalité naturelle chez les adultes. Avec l'arrêt complet des pêches, la biomasse de la population devrait augmenter si la mortalité naturelle chez les adultes était réduite de 80 %, et relativement rapidement si celle-ci était réduite de 85 %.

## 1. INTRODUCTION

Winter Skate (*Leucoraja ocellata*, Family Rajidae) is endemic to the Northwest Atlantic, occurring from Cape Hatteras to the Gulf of St. Lawrence and southern Newfoundland. The status of Winter Skate was first assessed by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) in May 2005. One of the four designatable units (DUs) identified by COSEWIC was the southern Gulf of St. Lawrence (sGSL) DU, which COSEWIC designated as Endangered (COSEWIC 2005).

Following the COSEWIC assessment, a Recovery Potential Assessment (RPA) of Winter Skate was conducted by the Canadian Department of Fisheries and Oceans (DFO 2005). The RPA of the sGSL DU indicated that adult abundance in this DU had declined by 96% from 1971 to 2002 and that this decline was due to increases in the natural mortality of adult skate. In contrast to natural mortality, fishing mortality was estimated to have declined to very low levels by the early 1990s. The sGSL population was projected to continue to decline under prevailing productivity conditions, even with no fishery removals.

COSEWIC re-assessed Winter Skate in 2015 and revised the DU structure. A new Gulf of St. Lawrence DU was defined composed of the former southern Gulf of St. Lawrence DU and the northern Gulf of St. Lawrence component of the former Northern Gulf – Newfoundland DU. This new DU was designated Endangered (COSEWIC 2015).

This document describes the 2016 RPA of the Gulf of St. Lawrence DU of Winter Skate. New information in this RPA includes an additional 10 years of survey data and fishery removals, new survey indices combining September Research Vessel (RV) survey data (1971 to 2014) and Northumberland survey data (2000 to 2014) using density-dependent habitat selection (DDHS) theory, results of ageing studies yielding length-at-age information, an age-structured population model, estimates of skate discard mortality in the sGSL and additional information on predation by grey seals as an important cause of the elevated natural mortality of adult skates.

## 2. LIFE HISTORY AND BIOLOGY

Life history and biology of Winter Skate are described in Swain et al. (2006a) and are briefly summarized here. Winter Skate in the sGSL differs from Winter Skate elsewhere, maturing at a much younger age and smaller size, and more closely resembling Little Skate (*L. erinacea)* in terms of life history characteristics. When information is lacking for sGSL Winter Skate, we assume that its characteristics are more similar to those of Little Skate than those of Winter Skate elsewhere. In the sGSL, Winter Skate occurs in shallow inshore areas in summer and moves offshore in winter (Darbyson and Benoît 2003). Like other skates, Winter Skate is oviparous, depositing a single egg in a horny capsule or purse. Based on the relationship among skate species between annual purse production and length at hatching (Holden 1973), annual fecundity for Winter Skate would be expected to be fewer than 50 purses per year. Average annual fecundity is reported to be 50 purses for the late-maturing form of Winter Skate (McPhie and Campana 2009*a*; Parent et al. 2008) and 30 for Little Skate (Frisk et al. 2002). We assume that annual fecundity for sGSL Winter Skate is about 30 egg cases. Gestation time within purses is reported to be 6 to 9 months and length-at-hatching for Little Skate is 9.5 to 10 cm (Scott and Scott 1988), values which we have used for sGSL Winter Skate.

Ageing has been conducted on 582 sGSL Winter Skate based on thin sections of their vertebrae (Fig. 1). Ageing methods were the same as those used by McPhie and Campana (2009*b*). Ageing conducted independently by a second reader also became available during the preparation of this report. However, ages were available only for a biased subsample of the vertebral sections. Thus, the age information used in this report is based on the ages obtained by the first reader using the entire sample of vertebrae. Ages are compared between the two readers in Appendix 1.

Based on a von Bertalanffy model fit to the length-at-age data (Fig. 1), $L\infty$ is estimated to be 77 cm. Estimated age at 50% maturity is about 5 years and length at 50% maturity is 40 cm for males and 42 cm for females (Kelly and Hanson 2013a).

## 3. THE DESIGNATABLE UNIT

COSEWIC revised the population structure of Winter Skate in its 2015 assessment. A new Gulf of St. Lawrence DU was established, composed of the former Southern Gulf of St. Lawrence population and the northern Gulf portion of the former Northern Gulf - Newfoundland population (COSEWIC 2015). It is our view that the new population structure proposed in the 2015 assessment is inappropriate.

Winter Skate in the sGSL are distinct from Winter Skate elsewhere (McEachran and Martin 1977; Swain et al. 2006a; Kelly and Hanson 2013a, 2013b). Compared to Winter Skate in other areas, those in the sGSL mature at a much smaller size and earlier age and have a much shorter maximum length (McEachran and Martin 1977; Kelly and Hanson 2013a), occur in shallower and warmer water in summer (Kelly and Hanson 2013b), and differ in morphological characters related to feeding (McEachran and Martin 1977). Given these striking differences, Kelly and Hanson (2013a) proposed that Winter Skate from the shallow waters of the sGSL may represent an undescribed endemic species distinct from *L. ocellata* elsewhere.

Winter Skate are rarely caught in surveys of the nGSL (58 individuals reported in 38 out of a total of 7,148 fishing tows in the August surveys of the nGSL (Gauthier and Nozères 2016)), compared to 3,000 individuals caught in 574 out of 6,242 tows in the September surveys of the sGSL. Furthermore, based on photographed specimens, catch depth and individual length-weight data, Gauthier and Nozères (2016) concluded that most of the Winter Skate reported from RV surveys of the nGSL appeared to be misidentified Thorny, Round and Smooth Skate, indicating that Winter Skate appear to be even rarer in the nGSL than previously thought. In addition, the few confirmed Winter Skate caught in the nGSL were of the typical late-maturing type, not the early-maturing sGSL type (Gauthier and Nozères 2016).

Gauthier and Nozères (2016) also noted that three Winter Skate were reported from the Upper St. Lawrence Estuary by Bigelow and Schroeder (1953; originally identified as Little Skate). Another confirmed Winter Skate was captured at a depth of 5 m in 1988 at Rivière-du-Loup, Upper St. Lawrence Estuary (Gauthier and Nozères 2016). This specimen, a mature male 49.5 cm in total length (TL), belonged to the early-maturing sGSL type.

In summary, there is no evidence to support the view that the sGSL type of Winter Skate occurs in the nGSL (NAFO Divisions 4RS). Extensive sampling of the nGSL indicates that Winter Skate occur very rarely in this region. The rare confirmed occurrences of Winter Skate in the nGSL (in Division 4R) belong to the typical late-maturing type of Winter Skate, not the early-maturing sGSL type. We conclude that the sGSL should be retained as a separate DU of Winter Skate, distinct from Winter Skate in other areas including the nGSL. The nGSL appears to be outside of the normal range of Winter Skate, with the few Winter Skate occurring in this area belonging to the typical late-maturing type.

The COSEWIC report alludes to the sGSL as NAFO Division 4T. The Northwest Atlantic Fisheries Organization (NAFO) Division 4T consists of the sGSL and the St. Lawrence Estuary. The information on Winter Skate in the sGSL DU is restricted to the sGSL proper (i.e., the areas covered by the annual September bottom-trawl survey of the sGSL and the summer bottom-trawl survey of the Northumberland Strait). Reported occurrences of Winter Skate in the Estuary are restricted to three individuals caught before 1953 and a single individual captured in 1988. This suggests that the Estuary may be outside of the normal range of sGSL Winter Skate, with the few reports from this area representing vagrants from the sGSL. The information presented in this assessment is restricted to Winter Skate in the sGSL.

# 4. DISTRIBUTION, ABUNDANCE AND BIOMASS

## 4.1 METHODS

### 4.1.1 Research Vessel (RV) survey

A bottom-trawl research vessel (RV) survey of the sGSL has been conducted each September since 1971 (for details see Hurlbut and Clay 1990 and Chadwick et al. 2007). This survey uses a stratified random design, with stratification based on depth and geographic region (Fig. 2). The target fishing procedure in all years was a 30-min tow at 3.5 knots. All catches were adjusted to a standard tow of 1.75 nautical miles.

Survey coverage was expanded in 1984 to include three inshore strata (401 to 403). Aside from the addition of these three strata, both the survey timing and survey area have remained constant since 1971. Analyses beginning in 1971 were restricted to the 24 strata fished since then (strata 415 to 439). Additional analyses restricted to the period after 1983 also included strata 401 to 403, inshore strata of potential importance to Winter Skate. The weight of stratum 402 was reduced by 50% because the western half of this stratum is not fishable in September due to the presence of lobster gear. Of the 27 strata, two (424 and 428) were not fished in 1978, while stratum 421 was not fished in 1983 and 1988 and stratum 402 was not fished in 1989, 1991, 1994 and 1995. In order to maintain a consistent survey area, in the years when these strata were not fished their weights were added to those of neighbouring strata in the same depth zone in calculations of stratified mean catch rates and distribution indices at length. In 2003, no stations were fished in strata 438 and 439. Predicted values for the mean catch rate in these strata were obtained using generalized linear models with terms for year and stratum. Models used a log link and assumed a Poisson error distribution allowing for overdispersion. This analysis was restricted to the 2002 to 2004 period to avoid effects of changes in distribution.

The research vessels conducting the survey were the *E. E. Prince* from 1971 to 1985, the *Lady Hammond* from 1985 to 1991, the *CCGS Alfred Needler* from 1992 to 2002, the *CCGS Wilfred Templeman* in 2003, both the *CCGS Alfred Needler* and the *CCGS Teleost* in 2004 and 2005, and the *CCGS Teleost* from 2005 to 2014. Tows conducted by the *E. E. Prince* used a *Yankee 36* trawl, while all other vessels used a *Western IIA* trawl. No differences in fishing efficiency for Winter Skate were detected between vessels or gears based on comparative fishing experiments (Benoît and Swain 2003; Benoît 2006).

Fishing was restricted to daylight hours (07:00 to 19:00) from 1971 to 1984 but was extended to 24 hours per day since 1985. Winter Skate are estimated to be more catchable at night than in the day, with the strength of this effect varying with length (Benoît and Swain 2003); individuals were estimated to be about 15 times more catchable at night at a length of 30 cm, declining to 3 times more catchable at night at a length of 65 cm. Consequently, night catches were adjusted to be equivalent to day catches using the length-dependent correction factors recommended by Benoît and Swain (2003).

Following Swain et al. (2006b, 2009), we grouped skates into two size classes: 42 cm and longer, roughly corresponding to the adult portion of the population, and 21 to 41 cm, roughly corresponding to juveniles two years of age (post laying of egg cases) and older. The exact cutoff point used for this grouping was constrained by the use of 3-cm sampling intervals in the 1970s and early 1980s. Winter Skate below 21 cm TL were very rare in September survey catches and were excluded from analyses. Swain et al. (2006b) concluded that these very small individuals were largely unavailable to the survey, occurring in inshore areas less than 20 m in depth.

Rates of change in abundance were estimated by regressing $\log_e$ survey catch rate against year. The percent change in abundance was estimated as $100*(\exp(b*\Delta t)-1)$ where $b$ is the regression slope and $\Delta t$ is the change in time (years).

Two indices of geographic range were examined; Design-Weighted Area Occupied (DWAO) and D95. DWAO is a measure of the area where catches were greater than 0. Because this index is based on an absolute threshold, it can be correlated with abundance even when geographic distribution is not density-dependent (e.g. contracting as abundance declines). D95 is the minimum area containing 95% of the population, and will change with abundance only if distribution spreads out as abundance increases and contracts as it declines (Swain and Sinclair 1994). Calculation of the indices is described by Swain et al. (2012). Indices were based on the 24 strata fished since 1971 (415 to 439).

### 4.1.2 Northumberland Strait (NS) survey

A bottom-trawl survey of the Northumberland Strait (NS) has been conducted in late July and early August since 2000. A No. 286 otter trawl with rockhopper footgear was used in all years except 2010 and 2011, which are omitted from the analyses presented here. Fishing was conducted during daylight hours, usually from 6:00 to 18:00. The standard tow in all years was a 15 minute tow at 2.5 knots. Winter Skate catches were grouped into juveniles and adults as described above, except in 2000 to 2002 when length composition data were not available. The survey area was divided into nine "blocks" or strata (1 to 3, 5 to 10), though coverage of the strata varied among years (Fig. 3). Stratum 8 was never sampled. Strata 1 to 3 and 5 were sampled in all years, though coverage of strata 3 and 5 was limited to their western halves in 2002 and coverage of stratum 2 was limited to its eastern extremity in 2005. Abundance and biomass indices were calculated based on strata 1 to 3 and 5 (sampled in all years) or strata 3 and 5 (the areas not covered by the September survey). Individuals less than 21 cm in TL were more common in the Northumberland Strait catches than in the September survey catches. Thus three length classes were examined for the Northumberland Strait survey: adults (≥42 cm), juveniles (21-41 cm) and recruits (<21 cm).

## 4.2 RESULTS

### 4.2.1 Geographic distribution in summer (July – September)

#### 4.2.1.1 September RV Survey

Adult Winter Skate were widely distributed in shallow (< 50 m) coastal waters of the sGSL in the 1970s and 1980s (Fig. 4). Densities were highest in Chaleur Bay, off the New Brunswick coast from Miscou to PEI, and between southeastern PEI and Nova Scotia in the Northumberland Strait. Catches of adult Winter Skate also occurred in shallow water east of the Magdalen Islands and along the north coast of PEI. Catch rates declined sharply in the 1990s and 2000s. By the late 2000s and early 2010s, catches of adult Winter skate were very rare. No adults were caught in the 2013 survey and a single adult was caught in 2014 (in stratum 402 in Northumberland Strait).

Geographic distribution was similar for juveniles, though they were less widely distributed than adults (Fig. 5). Juvenile densities were highest in the Northumberland Strait, along the east coast of PEI and along the New Brunswick coast from Miscou to PEI. Unlike adults, they rarely occurred in Chaleur Bay or off the Magdalen Islands in the 1970s and 1980s. They declined to very low levels by the early to mid-2000s and, like adults, were rarely caught in the late 2000s and early 2010s. No juveniles were caught in the standard survey strata (415 to 439) in 2013 and 2014, with a single individual caught in stratum 402 in Northumberland Strait in each of these years.

Both indices of geographic range indicated similar trends (Fig. 6). The geographic range of adults showed a progressive contraction beginning in the late 1980s (Fig. 6a, 6b). D95 of adults averaged 6,500 km$^2$ in the mid-1980s and declining to 377 km$^2$ in 2012, a 94% decline. Adults were absent from the standard survey area in 2013 and 2014. The time trend in geographic range differed for juveniles (Fig. 6c, 6d). D95 of juveniles was low in the early 1970s, averaging 800 km$^2$ in 1971 to 1975. It then increased to peaks in the early to mid-1980s (3,400 km$^2$) and early 2000s (3,150 km$^2$) before declining to low values in the late 2000s and early 2010s (775 km$^2$, 2007 to 2012). Like adults, juveniles were absent from the standard survey area in 2013 and 2014.

#### 4.2.1.2 Northumberland Strait Survey

Winter Skate were primarily caught in the western portion of Northumberland Strait since the start of this survey in 2000 (Fig. 7), even though these fish were also once common in eastern regions of the strait (Figs. 4, 5). Densities tended to be highest in Stratum 3 and the adjoining western portion of Stratum 5. Catch rates had declined to very low levels by 2012. In 2014, catches were largely restricted to a small region in eastern Stratum 3 and western Stratum 5.

Geographic distribution within the strait was similar between juveniles and adults, though the distribution of adults tended to be slightly more concentrated than that of juveniles (Figs. 8, 9). In the 2014 survey, catches of adults were restricted to a small region of Stratum 3, whereas the few tows catching juveniles were more widely distributed throughout Strata 3 and 5. Catches of recruits (<21 cm) were largely restricted to Stratum 3 (Fig. 10).

### 4.2.2 Seasonal distribution

In the sGSL, Winter Skate occur in shallow coastal waters in summer and early fall. The median temperature occupied by Winter Skate caught in the September RV survey is about 9°C, and median depths occupied vary between 24 m for skates under 33 cm TL and 32 m for those over 50 cm TL (Swain et al. 2006). In the Northumberland Strait survey, the median depths and temperatures occupied were 12 m and 16.5°C, respectively (Kelly and Hanson 2013b). In winter, these fish move offshore (Darbyson and Benoît 2003). In January, the highest densities appear to be at depths between 100 and 200 m along the slope of the Laurentian Channel, though Winter Skate appear to be distributed at lower densities over much of the Magdalen Shallows at depths over 40 m in this month (Clay 1991).

### 4.2.3 Habitat

Winter Skate was once widely distributed in shallow coastal waters of the sGSL, but its distribution has now contracted to the western portion of the Northumberland Strait. Within the Northumberland Strait, total biomass and the abundance of all life-history stages of Winter Skate (recruits, juveniles and adults) are highest in the area covered by Stratum 3 (Fig. 11; Kelly and Hanson 2013b), extending from Cape Tormentine in the east to Buctouche (NB) and West Point (PEI), in the west. All the Winter Skate caught in the 2014 Northumberland Strait survey were caught in this region. Based on Winter Skate distribution, this area appears to be the only important refuge remaining for Winter Skate in the sGSL.

The features contributing to the importance of this area are uncertain. Physical environmental factors such as temperature and depth do not appear to be involved. Based on the historic distribution of Winter Skate, physical environments suitable to Winter Skate are widespread throughout the shallow coastal zone of the sGSL. This suggests that biological interactions, such as predation or foraging, may be involved. The abundance of a piscivorous marine mammal, the Grey Seal *Halichoerus grypus*, has increased by an order of magnitude in the sGSL since the 1960s. In response, the summer distribution of prey with wide environmental tolerances, such as Atlantic Cod, White Hake and Thorny Skate, has shifted into deeper offshore areas where predation risk is relatively low in summer (Swain et al. 2015). However, depths greater than 50 m do not appear to be suitable for sGSL Winter Skate in summer. Risk of predation by Grey Seal is not as high in the western Northumberland Strait as it is in other inshore areas in summer (see below). This may account for the persistence of Winter Skate in this area. However, Winter Skate abundance has recently declined even in this area (Fig. 11), suggesting that even here predation rates may be too high to permit survival of this species (see below).

### 4.2.4 Abundance and biomass trends

#### 4.2.4.1 Biomass index

The biomass index for Winter Skate from the September RV survey (strata 415-439) was stable at a high level in the 1970s (Fig. 12). However, it has steadily declined since 1980, with an estimated 99% decline between 1980 and 2014. No Winter Skate were caught in strata 415 to 439 in 2013 and 2014.

Catch rates of Winter Skate in the NS survey (strata 1-3,5) were much higher than recent catch rates in the September RV survey (Fig. 12). Over the 2000 to 2014 period, the mean biomass index in the NS survey was 20 times the mean value of the index in the RV survey (despite a smaller swept area in the NS survey). Although this is partly due to the higher catchability of Winter Skate to the trawl used in the NS survey (see below), it also reflects the prevalence of preferred habitat of Winter Skate within the Northumberland Strait compared to the RV survey area (which is dominated by depths greater than those preferred by Winter Skate). Although the NS survey spans only a relatively short 15 year time period, there has been a highly significant decline of 78% in the biomass index for Winter skate since the start of this survey in 2000. There has also been a significant decline in the biomass index for NS Strata 3 and 5, an area not covered by the standard RV survey strata. Although this decline has been substantial (67% since 2000), the rate of decline in this area is only about 60% of the rate outside of the strait in strata 415 to 439.

#### 4.2.4.2 Adult abundance

The trend in adult abundance in the RV survey was similar to the trend in overall biomass. Adult abundance has been in decline since the late 1970s or early 1980s (Fig. 13). This decline was highly significant, corresponding to a 99% decline since 1982. Trawlable abundance of mature Winter Skate in strata 415 to 439 averaged 580,000 fish during 1971 to 1980, 29,000 fish during 2000 to 2009 and 5,000 fish during 2010 to 2014 (Table 1). Trawlable abundance is the mean catch per standard tow expanded to the survey area. Because catchability of Winter Skate to the RV survey gear is low (see below), actual abundance is expected to be greater than trawlable abundance. Nonetheless, no mature Winter Skate were caught in strata 415 to 439 in 2013 and 2014. Results were very similar including strata 401 to 403 since 1984 (Table

1). No mature Winter Skate were caught in strata 401 to 439 in 2013, but a single mature individual was caught in stratum 402 in 2014.

Estimated decline rates were lower based on catch rates in the NS survey, though data were only available for 2003 to 2009 and 2012 to 2014 (Fig. 13). Based on strata 1 to 3 and 5, the annual decline rate was marginally significant and corresponded to a 66% decline since 2003. Based on strata 3 and 5, the annual decline rate (corresponding to a 51% decline since 2003) was not statistically significant, but sample size was low. Based on strata 3 and 5, trawlable abundance averaged 148,000 fish during 2003 to 2006 and 88,000 fish during 2012 to 2014 (Table 1). Results were similar when including data from strata 1 and 2.

#### 4.2.4.3 Juvenile abundance

RV survey catch rates of juvenile Winter Skate were low in the early 1970s, increasing nearly 9-fold between then and the mid-1980s (Fig. 14). Juvenile catch rates then decreased sharply, resulting in a 99% decrease between the mid-1980s and 2014. Trawlable abundance of juveniles in strata 415 to 439 of the RV survey averaged 46,000 fish during 1971 to 1974, 183,000 fish during 1975 to 1985, 16,400 fish during 2003 to 2009 and 2,400 fish during 2010 to 2014 (Table 2). No juveniles were caught in these strata in 2013 and 2014. Results were similar when strata 401 to 403 were included, except that one juvenile was caught in stratum 402 in 2013 and 2014.

Juvenile catch rates in the NS survey were relatively high during 2005 to 2008 (strata 1 to 3, and 5) or 2006 to 2008 (strata 3 and 5) and low since 2009 (Fig. 14). However, the decline in juvenile catch rates was not significant over this short time period. Trawlable abundance of juveniles in strata 3 and 5 averaged 317,000 fish during 2006 to 2008 and 83,000 fish during 2009 to 2014 (Table 2).

## 5. ACCOUNTING FOR DENSITY-DEPENDENT HABITAT SELECTION

Habitat selection by marine fishes is typically density-dependent, with distribution expanding into marginal habitat as population abundance increases and contracting into optimal habitat as it declines (MacCall 1990). Because of this behavior, abundance indices from surveys can be "hyperstable" (changing more slowly than population abundance) if surveys focus on optimal habitat or "hyperdepleting" (changing more quickly than population abundance) if surveys exclude a disproportionate amount of optimal habitat. The optimal habitat of sGSL Winter Skate appears to be concentrated in the Northumberland Strait, in particular stratum 3 of the NS survey. The only long-term abundance index for sGSL Winter Skate is derived from the September RV survey. This survey does not cover a large proportion of the optimal habitat of Winter Skate and thus may be hyperdepleting. Winter Skate appears to have vanished from the RV survey area (strata 415 to 439) but persists in portions of the Northumberland Strait not covered by the RV survey. It may be important to take this contraction in distribution to areas outside of the RV survey into account when estimating the rate and extent of decline in this population.

We attempted to adjust for this bias in the RV abundance index using optimal foraging theory. This adjustment assumed that habitat selection by Winter Skate follows the ideal free distribution (IFD), a hypothesis from behavioural ecology that predicts the distribution of individuals and fitness between areas (Fretwell and Lucas 1970; Fretwell 1972). Given a number of assumptions, the IFD predicts that individuals will distribute themselves in a way that equalizes mean individual fitness among habitats. The assumptions underlying this prediction are:

1) individuals have ideal knowledge of the distribution of resources and competitors,

2) individuals are free to move between habitats without costs,
3) competition occurs among individuals in proportion to their local density, and
4) all individuals have equal competitive abilities.

Despite its oversimplifying assumptions, observations often match IFD predictions even when some of its assumptions are violated (e.g., Godin and Keenleyside 1984; Gillis and Kramer 1987; Morris and Davidson 2000; Swain and Wade 2003; Haugen et al. 2006).

If interference competition occurs (e.g., an individual's rate of prey consumption is reduced due to interactions with competitors), the effect of competitor density on fitness can be modelled as follows (Parker and Sutherland 1986):

$$W_i = Q_i n_i^{-m_i} \tag{1}$$

where $W_i$ is individual fitness in habitat i, $Q_i$ is intrinsic quality or suitability of habitat i (i.e. habitat quality when only one competitor occupies the habitat), $n_i$ is the number of competitors occurring in habitat i, and $m_i$ is the coefficient of interference in habitat i (usually $0 < m \leq 1$).

If individuals are distributed according to the IFD, then fitness is equalized across habitats, such that:

$$Q_j n_j^{-m_j} = Q_i n_i^{-m_i} \tag{2}$$

Taking the log of equation 2 and re-arranging gives:

$$\log(n_j) = \beta_0 + \beta_1 \log(n_i) \tag{3}$$

where $\beta_0 = -\log(Q_i/Q_j)/m_j$ and $\beta_1 = m_i/m_j$.

We fit equation 3 to the RV and NS data for the period 2000 to 2014, letting RV strata 415 to 439 represent habitat *i* and NS strata 3 and 5 represent habitat *j*. We then used the fitted relationship to predict abundance or biomass in habitat *j* in earlier years assuming that Winter Skate distribution conformed to the IFD.

Before fitting equation 3, catch rates were adjusted to the same swept area (10,000 $m^2$ = 1 ha) for both the RV and NS surveys. RV catch rates were also adjusted for the difference in catchability of Winter Skate between the RV and NS surveys. The trawl used on the NS survey has rockhopper foot gear whereas there are large rollers on the foot gear of the RV survey trawl. Edwards (1968) argued that the catchability of skates is very low to survey trawls with large rollers. This reflects a tendency by skates to remain on the bottom rather than to rise up off the bottom as the trawl approaches. Thus, given the large rollers on the foot gear of traditional survey trawls, these trawls tend to pass over rather than capture the skates in their path. Edwards(1968) suggested that catchability to survey trawls is about 10% for most skate species, though he argued that Winter Skate catchability is about 20%. Comparisons on the Scotian Shelf indicate that commercial rockhopper gear is about six times as efficient as the RV survey gear (the *Western IIA* trawl) at catching Winter Skate, with both adjusted to the same swept area (J.E. Simon, pers. comm., cited in the supplementary online material from Swain et al 2009).

We attempted to estimate the relative catchability of Winter Skate to the RV and NS surveys using data from 2000 to 2014, selecting tows from comparable regions of the two surveys. RV stratum 402 was considered equivalent to NS stratum 5. In the 2000 to 2014 survey period all RV tows in stratum 402 were located to the east of 63.6°W, so only tows east of this longitude were selected from stratum 5 for the analysis. Strata 432 and 433 were considered equivalent to NS stratum 6 and NS strata 7, 9 and 10, respectively. RV and NS stratum pairs were included in the analysis only in years when both the RV and NS strata were sampled (Table 3a). While total sample size was substantial, nonzero data were very sparse (Table 3b). Data were analyzed using the following generalized linear model:

$$E[c_{ijk}] = \mu_{ijk} = \exp(\alpha_i + \beta_j + \gamma_k) \quad (4)$$

$$Var[c_{ijk}] = \varphi\mu_{ijk} \quad (5)$$

where $c_{ijk}$ is the catch rate (fish per standard day tow) in stratum j in survey i in year k, $\mu$ is the mean expected catch rate, and $\alpha$, $\beta$ and $\gamma$ are vectors of parameters for survey, stratum and year (in practice, one fewer parameter than there are levels in each factor).

Despite the limited information, the estimated efficiency of the rockhopper gear in the NS survey relative to the *Western IIA* trawl was similar to the estimate from the Scotian Shelf (Table 4), i.e., exp(2.0167) = 7.51. While this parameter was not statistically significant at the 0.05 level in a two-sided test (Table 4), it approached significance (*P*= 0.06) in a one-sided test, arguably more appropriate as rockhopper footgear is expected a priori to be more efficient than roller footgear. Results were similar for biomass (not shown, relative efficiency = 8.37). The data were insufficient to support separate analyses for adults (four nonzero tows in the RV survey for strata 402, 432 and 433 in 2003 to 2014) and juveniles (10 nonzero tows for juveniles). Nonetheless, the estimates of relative efficiency were similar to the estimate for all sizes combined (9.36 for adults and 10.77 for juveniles). Given the very limited data available to measure relative fishing efficiency in the Northumberland Strait and the wide confidence intervals around the estimates from this area (Table 4), we used the estimate (value of 6) from the Scotian Shelf to adjust catch rates in the RV survey to be roughly equivalent to those in the NS survey.

The adjusted catch rates (kg/ha) in the RV survey (strata 415 to 439) and the NS survey (strata 3 and 5) are compared in Figure 15 assuming that distribution conforms to the IFD. In this case, habitat suitability (or individual fitness) should be the same in both habitats. We used the inverse of population trawlable biomass as an index of suitability. Based on this analysis, all Winter Skate in the sGSL population would be expected to occur in strata 3 and 5 of the Northumberland Strait when densities in these strata are 0.017 kg/ha or less. The estimated density in this area in 2014 was 0.14 kg/ha (95% CI: 0.035 – 0.246).

Equation 3 was first fit to the 2000 to 2014 data on biomass for all sizes combined. Mean catches of 0 in the RV data for 2013 and 2014 were replaced by half the smallest observed nonzero mean (i.e., 0.012 kg/ha in 2009) for this analysis. The regression was highly significant, accounting for 62% of the variation in log NS density (Fig. 16). Both the intercept and the slope were significant at the 0.05 level, despite the very low power of this test (Table 5). This regression was used to predict the density in NS strata 3 and 5 in years without observations (Fig. 17). Incorporating the estimated (2000 to 2009, 2012 to 2014) and predicted (1971 to 1999, 2010, 2011) trawlable biomass in Northumberland Strait strata 3 and 5 (402 of the RV survey), the decline rate since 1979 is estimated to be 98%, close to the 99% decline estimated using the RV data alone (Fig. 12).

In order to fit equation 3 to the 2003 to 2014 data on adult abundance, zero values for mean density in the RV survey in 2013 and 2014 and a near-zero outlier in 2011 were replaced by half the next lowest value (0.00396 in 2009). The regression was again highly significant, accounting for 71% of the variation in log NS density (Fig. 18). The slope was highly significant but the intercept only approached significance at the 0.05 level, though the power of this test was very low (Table 5). This regression was used to predict the density of adult Winter Skate in NS strata 3 and 5 in years without observations (Fig. 19). Accounting for the abundance of adults in the optimal NS habitat, the decline in adult abundance remained extreme at 97.6% since 1980, a negligible difference from the 99% estimate obtained using the RV data alone.

In order to fit equation 3 to the 2003 to 2014 data on juvenile abundance, zero values for mean density in the RV survey in 2013 and 2014 and a near-zero outlier in 2005 were replaced by half the next lowest value (0.00665 in 2007). The regression was not significant and accounted for a negligible proportion of the variation in log NS density of juveniles (Fig. 20, Table 5). Thus, there was no support for the hypothesis that the distribution of juveniles among habitats conformed to the IFD, though the power of this test was very low.

In summary, based on the very limited information available, the densities of Winter Skate in the RV survey area and the optimal habitat in the Northumberland Strait, and their changes over time, are consistent with the IDF, both for total biomass and adult abundance. The relationship between densities in these two areas in recent years were used to predict densities in the Northumberland Strait in earlier years. The extreme declines in total biomass and adult abundance, estimated based on the RV data alone, persist when the region of the Northumberland Strait not sampled by the RV survey is incorporated in the analysis. In contrast, the relationship between densities of juvenile Winter Skate in the Northumberland Strait and the RV survey area does not provide support for behavior conforming to the IFD. This may reflect the very limited information available for this test, which was restricted to the recent period when catch rates in the RV survey were very low with little contrast among years. Consequently, it is not possible to estimate the long-term decline of juvenile Winter Skate accounting for densities in the area of the Northumberland Strait unsampled prior to 2000. Nonetheless, the failure to detect juveniles in the RV survey in recent years and the low densities in the Northumberland Strait in these years (Fig. 14) indicate that the decline in juvenile densities has also been extreme.

## 6. FISHERY CATCH

There has been no directed fishing for skates in the southern Gulf of St. Lawrence. However, skates, including Winter Skate, are incidentally captured in commercial fisheries directed at other species. Most of these skates are discarded, though a small proportion is landed annually (Benoît, 2013a). Winter Skate is incidentally captured in the commercial scallop fishery as a result of considerable spatial-temporal overlap in their respective distributions (Benoît et al., 2010a; DFO, 2010). Winter Skate is also captured in groundfish fisheries, most notably those directed at the coastal flatfish species, Winter Flounder (*Pseudopleuronectes americanus)* and Yellowtail Flounder (*Limanda ferruginea)* (Benoît, 2006, 2013a). Though the distribution of the southern Gulf lobster fishery overlaps with that of Winter Skate, the current lobster trap design (based on a cage) likely prevents the incidental capture of skate. The wooden-lat traps that were used previously in that fishery may have incidentally captured Winter Skate, however the data do not exist to evaluate this possibility. In this section, we provide estimates of Winter Skate landings, as well as discard amounts and discard mortality rates for southern Gulf scallop and groundfish fisheries.

The main data to estimate fishing-induced mortality of Winter Skate come from four sources; landings statistics, regulatory at-sea fisheries observer programs for groundfish and shrimp fisheries, a one-off scientific at-sea observer project to quantify Winter Skate bycatch in the scallop fishery during 2006 to 2008, and the annual RV survey of the southern Gulf. Estimating fishing-induced mortality of Winter Skate presents a number of challenges. First, skate landings are not identified to species and the species composition of those landings needs to be estimated using additional sources of information (Benoît, 2013a, 2013b). Skates are also not routinely, and in some instances, not reliably, identified to species by fisheries observers. The species composition of skate catches reported by observers therefore also needs to be estimated. Second, at-sea observer programs can suffer from non-random deployment of observers (deployment effects) and changes in harvester behaviour when an observer is present (observer effects), which can affect the reliability of the inferences that are drawn (Benoît and Allard 2009). Third, the size composition of either landed or discarded skates is not available, except for the scallop fishery in the mid -2000s. Fourth, because the majority of incidentally captured skate are discarded, a discard mortality rate is required to estimate losses. Fifth, sufficient at-sea observer data to estimate annual Winter Skate discards are only available since 1991 and several assumptions are required to derive estimates for prior years. The methods described below attempt to address all of these challenges and to produce estimates of Winter Skate losses based on the best available science and that best reflect the uncertainty associated with the estimation.

## 6.1 METHODS

### 6.1.1 Bycatch in the scallop fishery

An at-sea sampling project aboard commercial scallop fishing vessels was conducted during the 2006 to 2008 scallop fishing seasons (Benoît et al. 2010a). The goal was to estimate the amount of Winter Skate captured in the fishery, as well as to assess the potential survival rate of discarded skate. A total of 624 fishing sets over 24 trips (1 day/trip) were observed in the commercial scallop fishery from 2006 to 2008. Samples were obtained in scallop fishing areas (SFA) 21A, 21B, 21C, 22, 23, and 24. During the at-sea sampling, individual Winter Skate were measured and their condition (degree of injury, on a scale of none to major, and 'liveliness', on a scale from very lively to moribund) was assessed (details in Benoît et al. 2010b). These condition values are good predictors of the post-release survival of discarded skates and other fish species (Benoît et al. 2012). There has not been any monitoring of bycatch in the southern Gulf scallop fishery other than during this 2006 to 2008 project.

Benoît et al. (2010a) used design-based estimation to calculate the number of Winter Skate discarded annually in SFAs 21 to 24 in the 2006 to 2008 fisheries. They then adjusted their estimates for scallop fishing trips occurring in other SFAs of the southern Gulf and applied a 90% discard survival rate that was derived using the condition observations and discard survival experiments conducted on trawl-caught skates (Benoît et al. 2010b, 2012). This resulted in an estimate of 402 juveniles (73 to 600, 95% confidence Interval) and 88 adults (16 to 132) killed in the 2007 southern Gulf scallop fishery (the year with the highest mean catches in their study) (DFO 2010). For that time period, this fishing mortality was considered small relative to natural mortality.

To estimate Winter Skate discards from 1971 to 2014 required extrapolating the results of the 2006 to 2008 study. A metric of scallop fishing mortality would be the ideal basis for extrapolation because if Winter Skate catch is truly incidental, the imposed fishing mortality should be proportional to the fishing mortality of the directed species, all else being equal although changes in the relative distributions of the fishery and Winter Skate and changes in fishing gear will affect this proportionality. Scallop landings are unfortunately the only basis for extrapolation given that there is no quantitative assessment for sGSL scallops, there were no logbooks in this fishery prior to 2000, and effort reports in the subsequent logbooks are not fully trusted. The landings themselves are subject to a likely time-varying bias, since landing statistics are based on declared sales, which are acknowledged to be an underrepresentation of actual landings (M. Lanteigne, DFO Moncton, pers. comm). Furthermore landings constitute a poor surrogate for fishing mortality given, amongst other things, past changes in fishing gear and in fishing areas (e.g., in response to the imposition of buffer zones and closed areas).

Nonetheless, coarse patterns in the landings, notably a decline during the 1990s and early 2000s, are consistent with perceived changes in fishing effort (M. Lanteigne, DFO Moncton, pers. comm) and thereby provide a means to at least estimate the general scale and coarse trends of Winter Skate bycatch in the fishery over the decades.

Winter Skate discards in the scallop fishery were estimated using the following equation:

$$\hat{d}_t = L_t \cdot \frac{\bar{d}_{2006-2008}}{\bar{L}_{2006-2008}} \cdot \frac{R_t}{R_{2007}} \qquad (6)$$

where $\hat{d}_t$ is the estimated total amount of Winter Skate discarded (tonnes) in the fishery in year *t*, $L_t$ is the reported landings of scallops in year *t*, $\bar{d}_{2006-2008}$ is the estimated average biomass of Winter Skate discarded in 2006 to 2008 based on the at-sea sampling project, $\bar{L}_{2006-2008}$ is the average scallop landings in 2006 to 2008, and $R_t$ is the smoothed RV survey trawlable biomass of Winter Skate in *t*. In this equation, discards in a given year are assumed to be proportional to scallop landings and the discard rate estimated during 2006 to 2008, adjusted by the abundance of Winter Skate relative to its estimated value in 2007, the midpoint of the at-sea sampling project. A loess function fit to the annual RV survey stratified mean trawlable biomass estimates was used to minimize the influence of year effects in $R_t$.

Uncertainty in $\hat{d}_t$ was estimated using a Monte Carlo simulation based on bootstrapping (Efon and Tibshirani 1993) for $\bar{d}_{2006-2008}$ and $R_t$. Parametric bootstrapping was used for the former, drawing simulated values from a normal distribution with a mean of $\bar{d}_{2006-2008}$ and a coefficient of variation of 0.25, which produces values comparable to those observed in 2006 to 2008. Non-parametric bootstrapping was used to simulate the variability in $R_t$, by first drawing individual RV survey sets with replacement within strata and years and calculating annual trawlable biomass estimates for 1971 to 2014. The error simulated in this manner produced confidence intervals that were very comparable to the analytical confidence interval estimates (Fig. 21). During each bootstrap iteration, a loess function was fit to the bootrapped trawlable biomass estimates. Variability in those loess estimates across iterations was used as an estimate of the variability in $R_t$. One thousand iterations were used, which was sufficient to produce stable estimates of the confidence intervals. Here and throughout this section, the 2.5th and 97.5th percentiles of the bootstrapped distributions were used as the estimates of the lower and upper confidence intervals respectively.

### 6.1.2 Bycatch in groundfish and shrimp fisheries

Fisheries observer surveys are the only reliable long-term source of information on skate discards in the sGSL. Target observer coverage levels are set by fishery and generally vary between 5 and 15% of fishing trips, though actual coverage levels have often been lower (Benoît and Allard, 2009). The main sampling unit for the surveys are individual fishing trips and deployments are effected on a fishery-specific basis. Observers provide reports for individual fishing hauls that include information on the geographic position, depth, date, time, duration, and catch composition. The masses of both retained and discarded catches are recorded for each captured taxon. Given the inconsistencies in the identification of individual skate species in the at-sea observer data, catches of skates were pooled into an unspecified skate category for the analyses and species composition was estimated in a subsequent step (details below).

There has been annual coverage by observers in all groundfish fisheries and the shrimp fishery in the sGSL since 1991 (Table 6). The total number of trips sampled annually by observers across all fisheries in the sGSL has varied from 416 in 1991 when fishing effort was elevated, to just over 100 in more recent years, which have been characterized by considerably reduced effort (Table 7). In general, half or more of observed trips annually have reported some amount of discarding of skates. In addition, in each year there has been a small number of observed trips that reported catches of skates that were retained by the harvesters.

To evaluate whether bycatch of skates can be reliably estimated from observer data in light of possible deployment and observer effects, we estimated the landings predicted using the retained catches reported by observers. These estimates were then compared to the landings reported from dockside catch monitoring, which are considered accurate, as a way of validating the catch and discard estimation process. Reasonable correspondence between estimated and reported landings would suggest that that the observer data are reliable for skates and that estimated discards are therefore also likely accurate (Benoît, 2013a).

Annual total catches of skates in sGSL fisheries, both retained and discarded amounts, were estimated using the ratio of skate and commercial species catches for observed fishing hauls, and reported landings for the commercial species (details below). Design-based estimation of catches from observer data (e.g., Rochet and Trenkel 2005; Cotter and Pilling, 2007) was not possible because the deployment of fisheries observers to fishing trips in sGSL fisheries has followed an undocumented deployment scheme (details in Benoît and Allard 2009). In some years and fisheries at the beginning of the program, or when fishing effort was small, only a small number of trips were sampled by observers. For these instances, data from consecutive years were pooled in order to estimate the catch ratios (details in Table 6).

There are two catch categories, retained (*c=r*) and discarded (*c=d*) catch. Let $\hat{b}_{c,t}$ be the estimated total biomass of captured skate in the sGSL in catch category *c* and year *t*. The value of $\hat{b}_{c,t}$ was estimated as:

$$\hat{b}_{c,t} = \sum\left[\left(\frac{\sum_k B_{c,k,f,t}}{\sum_k \sum_s C_{s,k,f,t}}\right) \sum_s L_{s,f,t}\right] \qquad (7)$$

where $B_{c,k,f,t}$ is the mass of skates in catch category *c* of observed fishing haul *k* in fishery *f* and year *t*, $C_{s,k,f,t}$ is the retained catch of commercial fish species *s* reported by observers for haul *k*, and $L_{s,f,t}$ $L_{s,f,t}$ is the landed amount of species *s* in fishery *f* and year *t* taken from the official landings records. The estimates were stratified by fishery because this is the level at which decisions on fishery observer allocations are made and it also accounts for differences in bycatch rate between fisheries. Uncertainty in $\hat{b}_{c,t}$ was simulated using a non-parametric bootstrap (Efron and Tibshirani, 1993) in which observed fishing trips within fisheries *f*, and years *t*, were sampled with replacement and bootstrapped values of $\hat{b}_{c,t}$were calculated using equation 7 for each iteration. Five thousand iterations were used for the simulation. Percentiles of the bootstrapped distribution were used as the 95% confidence intervals for $\hat{b}_{c,t}$ as noted above. This bootstrapping routine was also included as part of a broader Monte Carlo simulation that involved bootstrapping for other components of the Winter Skate discard estimation process with the aim of producing final estimates that best reflect the overall estimation uncertainty. The bootstrap routines for those other components are described below.

### 6.1.2.1 Estimating species-specific annual landings and discards (1991 to 2014)

Skate catches reported by fisheries observers were disaggregated into the constituent species using an empirical baseline-category logits model (Agresti 2002) that uses capture depth and date to predict the species composition of mixed groundfish catches (Benoît 2013b). In the sGSL three skate species make up well over 99% of catches in the annual RV survey; Winter Skate, Thorny skate (*Amblyraja radiata*) and Smooth Skate (*Malacoraja senta*). The seasonal distributions of these species differ as a function of depth, though there is some overlap between them.

Given that a skate has been observed in haul *k*, let $\pi_{j,k} = P(Y = j \mid g_k, t_k)$ be the probability that skate *Y* is of species *j*, given that it was caught at depth *g* (in meters) and at time *t* (day-of-year). Now define the linear model:

$$log\frac{\pi_{j,k}}{\pi_{J,k}} = \beta_{0,j} + \beta_{1,j}\, g_k + \beta_{2,j}\, g_k^2 + g_k \sum_{p=1}^{3}\left(\eta_{p,j}\, sin\left(p\omega t_k - \delta_{p,j}\right)\right);\; j = 1, J-1 \qquad (8)$$

where $\omega = {}^{2\pi}/_{365}$ is the fundamental annual frequency, *p* defines the cycle frequency (annual, *p* = 1; bi-annual, *p* = 2; tri-annual, *p* = 3), *J* = 3 is the number of skate species in the sGSL and $\beta_{0,j}$, $\beta_{1,j}$, $\beta_{2,j}$, $\eta_{p,j}$, and $\delta_{p,j}$ are parameters estimated using RV survey data. The left-hand part of equation 8 is the logit for the response probability of species *j* relative to that of a chosen baseline species *J*. Details on the model choice, fitting, validation and model-based predictions are available in Benoît (2013b).

Predicted response probabilities $\hat{\pi}_{j,k,f,t}$ for observed fishing haul *k* in fishery *f* and year *t* were obtained using the logit-transformation of equation 8:

$$\hat{\pi}_{j,k,f,t} = \frac{exp\left(\boldsymbol{\beta}_j'\mathbf{X}_{k,f,t}\right)}{\sum_{h=1}^{J} exp\left(\boldsymbol{\beta}_h'\mathbf{X}_{k,f,t}\right)};\, for\; j = 1, J\; with\; \boldsymbol{\beta}_J = 0 \qquad (9)$$

where $\boldsymbol{\beta}_j$ and $\mathbf{X}_{k,f,t}$ are shorthand for the vector of estimated parameters for species *j* and the matrix of explanatory variables for set *k*, respectively. From equations 7 and 9, the total annual biomass of skate species *j* for the catch category *c* was estimated as:

$$\hat{b}_{j,c,t} = \sum_f \left[\left(\frac{\sum_k B_{c,k,f,t}\, \hat{\pi}_{j,k,f,t}}{\sum_k \sum_s C_{s,k,f,t}}\right) \sum_s L_{s,f,t}\right] \qquad (10)$$

For simplicity, hereafter the estimated total discards (*c* = *d*) of Winter Skate in year *t* are represented by

$\hat{d}_t = \hat{b}_{j=Winter\ Skate, c=d, t}$.

For the retained catch category (*c* = *r*), equation 10 estimates the landings of each skate species based on observer reports. Here these are termed initial estimates. Because reported landings are perhaps a more accurate representation of actual landings, we also estimated 'adjusted' species-specific skate landings as:

$$\hat{L}_{j,t} = L_{skate,t}\, \frac{\hat{b}_{j,c=r,t}}{\sum_{j=1}^{3} \hat{b}_{j,c=r,t}} \qquad (11)$$

where $\hat{L}_{j,t}$ is the estimated amount of the official skate landings, $L_{skate,t}$, that is comprised of skate species *j*, in year *t*.

Uncertainty in the response probabilities in equation 9 was simulated by re-sampling the data used to fit equation 7 and obtaining a new model fit for each Monte Carlo iteration (details in Benoît 2013b). Combined with the empirical bootstrap described for equation 7, the Monte Carlo simulation for equation 10 therefore incorporates uncertainty related to the estimation of catch amounts and the estimation of catch composition.

The remaining source of Winter Skate catches is the sentinel fisheries of the sGSL. These fisheries have 100% observer coverage and consequently total annual retained and discarded catches of Winter Skate were obtained directly from the data.

### 6.1.2.2 Estimating species-specific annual landings and discards (1971 to 1990)

Different assumptions were required to estimate annual landings and discards of Winter Skate for the period from 1971 to 1990 given the absence of at-sea fisheries observer data. For that period, annual landings of Winter Skate were estimated as:

$$\hat{L}_{Winter\ Skate,t} = L_{skate,t}\,\bar{r} \qquad (12)$$

where $\bar{r} = {}^{1}/_{24} \sum_{t=1991}^{2014} \frac{\hat{b}_{j=Winter\ Skate,c=r,t}}{\sum_{j=1}^{3} \hat{b}_{j,c=r,t}}$

that is, as a product of total skate landings and the average estimated proportion of Winter Skate in landings based on the estimates derived using the observer data (previous subsection). An average proportion appeared justified as there was no temporal trend in the annual estimates for 1991 to 2014 (see results below). Uncertainty in $\bar{r}$ and therefore $\hat{L}_{Winter\ Skate,t}$ was simulated using the bootstrapped values for $\hat{b}_{j,c=r,t}$ from equation 10 (see previous subsection).

Winter Skate annual discards for 1971 to 1990 were estimated using one approach for the major fisheries that capture that species and another for fisheries with fewer Winter Skate discards. Three commercial fisheries produced the majority (typically >90%) of estimated Winter Skate discards over the 1991 to 2014 period: the coastal flatfish mobile-gear fishery directed at Winter Flounder and Yellowtail Flounder, the mobile-gear offshore flatfish fishery directed at American Plaice (*Hippoglossoides platessoides*) and Witch Flounder (*Glyptocephalus cynoglossus*), and the Atlantic Cod (*Gadus morhua*) fishery. Assuming that bycatch of Winter Skate in these fisheries is completely incidental and that there were no changes in the relative catchability and availability of the target species and Winter Skate to the fisheries, Winter Skate discards were assumed to be generated by a fishing mortality that was proportional to that of the target species. Using the Baranov catch equation, this was formalized as:

$$\hat{d}_{t,s} = \frac{b_s F_{t,s}}{b_s F_{t,s} + M_t}\big(1 - \exp(-(b_s F_{t,s} + M_t)\big)R_t \qquad (13)$$

where $\hat{d}_{t,s}$ is the estimated amount of Winter Skate discards in year *t* in the fishery directed at commercial fish species *s*, $F_{t,s}$ is the instantaneous fishing mortality of species *s* estimated in the assessment for that species, $b_s$ is the proportionality coefficient for the fishing mortality of Winter Skate and species *s*, which is assumed to be time invariant, $M_t$ is the natural mortality of Winter Skate for those ages most commonly captured as bycatch and $R_t$ is the smoothed RV survey trawlable biomass of Winter Skate in year *t* (as in equation 6). Non-linear least squares estimation was used to derive estimates of $b_s$ from equation 13 given estimates of $\hat{d}_{t,s}$ derived from the at-sea observer data (described above) and existing estimates of $F_{t,s}$ and $M_t$ for the years (*t*) 1991 to 2014. The resulting estimates of $b_s$ and available estimates of $F_{t,s}$ and $M_t$ were then used to estimate $\hat{d}_{t,s}$ for the years (*t*) 1971 to 1990 using equation 13.

Uncertainty in the values of $b_s$was simulated using a Monte Carlo simulation for *t* = 1991 to 2014. For each of 5,000 simulation iterations, simulated values of $\hat{d}_{t,s}$ and $R_t$ were drawn with replacement from their respective bootstrapped distributions (see section 6.1.2.1 and 6.1.1), values for $F_{t,s}$ were drawn from their respective MCMC distributions generated as part of the assessment model fitting procedures (see sources in the table below), and a bootstrapped value of $b_s$ was estimated using equation 13.

Uncertainty in the values of $\hat{d}_{t,s}$ for *t* = 1971 to 1990 was then simulated using a similar approach, this time by drawing values of $R_t$, $b_s$ and $F_{t,s}$ from their respective bootstrapped or

MCMC distributions. The 2.5th and 97.5th percentiles of the resulting bootstrapped distribution were taken as the 95% confidence intervals for $\hat{d}_{t,s}$ for $t$ = 1971 to 1990.

The following instantaneous fishing mortality series were used for $F_{t,s}$ (Fig. 22):

| *Fishery (s)* | *Commercial stock* | *Ages* | *Years* | *Source* |
|---|---|---|---|---|
| Coastal Flatfish | Winter Flounder[1] | 6+ | 1973 to 2011 | Morin et al., 2012 |
| Offshore Flatfish | American Plaice | 10-14 | 1976 to 2011 | Morin et al., 2013 |
| Cod mobile | Atlantic Cod | 5-8 | 1971 to 2014 | Swain and Benoît, 2015 |

[1] the instantaneous fishing mortalities from the assessment were adjusted to reflect mortality in mobile gear only.

The fishing mortality for Winter Flounder was assumed to represent the average directed fishing mortality in the coastal flatfish fishery because no estimates of fishing mortality for Yellowtail Flounder were available at the time of this assessment. The ages 6+ series was chosen because it more closely represents the sizes of captured Winter Skate. The fishing mortality for American Plaice was assumed to represent the average directed fishing mortality in the offshore flatfish fishery because the spatial distribution of plaice resembles that of Winter Skate more closely than does the distribution of Witch Flounder. The age groups for the plaice and cod fishing mortality series were also chosen to reflect the sizes of Winter Skate captured, though the general trends in the series are comparable to those for other age groups; estimates of Winter Skate discards would therefore not be very sensitive to this choice. The $F_{t,s}$ series for the flatfish fisheries were extended back to 1971 by assuming that the first estimated fishing mortality value was representative of the prior years.

Initial analyses were undertaken assuming the following values for $M_t$: 0.2 (1971 to 1989), 0.6 (1990 to 1999) and 0.7 (2000 to 2014). Based on preliminary population model estimates of Winter Skate natural mortality (details further below), updated discard estimates were generated with the following updated values for $M_t$: 0.13 (1971 to 1977), 0.41 (1978 to 1984), 0.75 (1985 to 1991), 1.03 (1992 to 1998), 0.87 (1999 to 2005) and 0.85 (2006 to 2014). Both initial and updated discard estimates are presented in the results. The initial discard estimates were used in preliminary population model runs and the updated estimates were used in the final model runs, though both produced similar estimates of Winter Skate fishing mortality.

The remaining fisheries typically produced <10% of the annual Winter Skate discards for 1991 to 2014. Annual discards from these fisheries were summed separately for fixed and mobile-gear fisheries and the annual proportion of total Winter Skate discards caught by these two groups of fisheries was calculated. The mean proportions for the period from 1991 to 2000 were then used to prorate the annual discard estimates for the three major fisheries to obtain total discard estimates for 1971 to 1990. The 1991 to 2000 period was chosen to calculate the mean proportions because the estimated proportions were non-stationary (see results) and this period was assumed to better reflect fishing mortality prior to 1991. Uncertainty related to this step of the estimation procedure was simulated by drawing values of $\hat{d}_{t,s}$ for $t$ = 1991 to 2000 with replacement from their bootstrapped distributions, calculating the mean proportions and applying them to the bootstrapped discard estimates for the three major fisheries for each iteration of the Monte Carlo simulation.

#### 6.1.2.3 Estimating annual discard survival rates

Not all discarded Winter Skate die as a result of capture, handling and release. Discard mortality rates can vary as a result of technical (e.g., gear, handling), environmental (e.g., temperature gradients experienced during capture) and biological (e.g., size, sex) factors (Davis 2002; Benoît et al. 2010b, 2013). To account for this variability using the available information, annual discard mortality rates for the groundfish and shrimp fisheries were estimated using a single estimate for fixed-gear fisheries and time-varying estimates that account for the main factors affecting mortality rates in mobile-gear fisheries.

The only available information on Winter Skate discard mortality in a fixed gear fishery comes from an unpublished study for the New England monkfish gillnet fishery (Sulikowski et al., unpublished data). A total of 239 Winter Skate captured in a total of 11 fishing sets in 2014 (July, September and October) and 2015 (July and August) were held in sea cages for typically three days, but up to 12 days to assess survival. The nets in this fishery have a 4 inch mesh size and are set at a mean depth of around 120 m for one to seven days (modal soak duration 5 days). Based on these data, the estimated survival rate for Winter Skate discarded in this fishery is 89%, with a 95% confidence interval of 84%-92% (H. Benoît, unpublished data).

Benoît (2013a) used the approach of Benoît et al. (2012) to estimate annual discard mortality rates (and associated uncertainty) for Winter Skate captured in sGSL mobile gear fisheries during 1991 to 2011. Those analyses were extended here to include the period up to 2014. Briefly, the approach uses information on Winter Skate discard amounts and factors that have been shown to affect skate discard survival (total catch, sea surface temperature and catch handling time) for individual fishing sets covered by at-sea observers, combined with results from discard survival experiments, to calculate annual weighted survival estimates and associated uncertainties (see Benoît et al. 2012 for details). An overall annual discard survival rate for Winter Skate captured in mobile-gear fisheries was thus estimated for the period 1991 to 2014. Annual discard survival rates were also estimated separately for the coastal flatfish, offshore flatfish and cod mobile-gear fisheries for the 1990s. These values were used to calculate a mean survival rate for each fishery that was assumed to be applicable to discarded Winter Skate in the years prior to 1991. Note that the mean survival rate for the cod fishery was based on estimates for 1991 to 1993, prior to the cod fishery moratorium. A mean value for the overall mobile-gear survival rate for the 1990s was likewise calculated.

Overall annual discard survival rate estimates ($\hat{U}_t$) for Winter Skate were estimated as averages of fishery (or fishery group) specific survival rates ($\bar{u}_x$) weighted by fishery (or group) specific estimates of Winter Skate discard amounts ($\hat{d}_{t,x}$).

For the 1971 to 1990 period:

$$\hat{U}_t = \frac{\bar{u}_{cf}\hat{d}_{t,cf} + \bar{u}_{of}\hat{d}_{t,of} + \bar{u}_{codm}\hat{d}_{t,cod}pmob_t + \bar{u}_{mob}\hat{d}_{t,mob} + \hat{u}_{fixed}(\hat{d}_{t,fixed} + (1-pmob_t)\,\hat{d}_{t,cod})}{\hat{d}_{t,cf} + \hat{d}_{t,of} + \hat{d}_{t,cod} + \hat{d}_{t,mob} + \hat{d}_{t,fixed}} \tag{14}$$

where $\bar{u}_x$is the mean survival rate for fishery *x* with x = *cf* is the coastal flatfish fishery, x = *of* is the offshore flatfish fishery, x= *codm* is the cod mobile-gear fishery, x = *mob* represents the remaining mobile gear fisheries and x = *fixed* represents the remaining fixed gear fisheries, $\hat{u}_{fixed}$ is a single estimate for survival rate from the fixed gear, and *pmob$_t$* is the proportion of cod landings in year *t* coming from the mobile-gear sector (Fig. 23).

For the 1991 to 2014 period,

$$\hat{U}_t = \frac{\hat{u}_{t,mob}\,(\hat{d}_{t,cf} + \hat{d}_{t,of} + \hat{d}_{t,codmob} + \hat{d}_{t,mob}) + \ \hat{u}_{fixed}\,(\hat{d}_{t,fixed} + \hat{d}_{t,codfixed})}{\hat{d}_{t,cf} + \hat{d}_{t,of} + \hat{d}_{t,codmob} + \hat{d}_{t,mob} + \hat{d}_{t,fixed} + \hat{d}_{t,codfixed}} \tag{15}$$

where $\hat{d}_{t,codmob}$ and $\hat{d}_{t,codfixed}$ are the estimated Winter Skate discards in the cod mobile-gear and fixed-gear fisheries, respectively.

Uncertainty in $\hat{U}_t$ was estimated using a Monte Carlo simulation in which uncertainty in $\hat{u}_{t,x}$, $\hat{u}_{fixed}$ and $\hat{d}_{t,x}$ was simulated. Uncertainty in $\hat{u}_{t,x}$ was simulated using the Monte Carlo simulation described in Benoît et al. (2012) and updated in Benoît (2013a). Uncertainty in $\hat{u}_{fixed}$ was simulated using an empirical bootstrap of the original survival experiment data and uncertainty in $\hat{d}_{t,x}$ was simulated as described above. Again, 5,000 simulation iterations were used and the 2.5th and 97.5th percentiles of the resulting bootstrapped distribution were taken as the 95% confidence intervals for $\hat{D}_t$.

## 6.2 RESULTS

### 6.2.1 Bycatch in the scallop fishery

Reported scallop landings in the sGSL were over 5,000 t in 1971, declining to around 3,000 t for most of the period from 1972 to 2000, and then declining further to near 1,000 t annually since 2001 (Fig. 24). As a result of these changes in landings, and the continuous decline in the relative abundance of Winter Skate since the early 1970s (Fig. 21), estimated discards of Winter Skate in the scallop fishery declined from over 100 t in 1971 to 1972, to around 50 t annually from the mid-1970s to mid-1980s and again to around one tonne annually since 2005 (Fig. 24; Appendix 2).

The reliability of the discard estimates prior to the mid-2000s is uncertain given, amongst other things, the high degree of extrapolation of the results of the 2006 to 2008 at-sea scallop fishery sampling project, lack of reliability for the scallop landings, and the tenuous assumptions used in the extrapolation (e.g., proportionality of discards to scallop landings). In particular, past changes in the gear used in the fishery and the introduction of closed areas in the mid-2000s are likely to have affected the catchability and availability of Winter Skate to the commercial fishing gear. Though the estimates for the mid-2000s may also be inaccurate, they result in fishing mortality rates that are sufficiently low that even if the estimates were incorrect, discard mortality in the scallop fishery is unlikely to be a significant component of Winter Skate mortality (DFO 2010).

Benoît et al. (2010a) assumed a 90% discard survival rate based on condition observations made during the 2006 to 2008 at-sea scallop fishery sampling project and discard survival experiments conducted on trawl-caught skates (Benoît et al. 2010b, 2012). There is no information available to gauge whether this value is representative of Winter Skate discard survival rates for other periods.

### 6.2.2 Bycatch in groundfish and shrimp fisheries

Skate landings in the sGSL were highest in 1974 and 1975 at around 130 t (Fig. 25; Table 8). Annual landings varied around 10 to 60 t from the mid-1970s to the mid-1980s and again from the mid-1990s to the mid-2000s, and were generally around or below one tonne in intervening and subsequent years. Landings predicted from the retained catches reported by fisheries observers generally matched the reported landings, though there was considerable uncertainty in the estimated landings due to the small number of observed trips with reported landings (Fig. 25; Tables 7 and 8). This result suggests that the data and method used to estimate landings, and by extension discards, are generally reliable.

Adjusted estimates of Winter Skate landings during 1991 to 2014 varied over time, though they tended to be greater in the 1990s compared to the 2000s (Table 8; Fig. 26). In most years in the 2000s, estimated Winter Skate landings were less than 500 kg. The estimated proportion of Winter Skate in sGSL skate landings varied without trend over the 1991 to 2014 period, with no significant autocorrelation at any lag (Fig. 27). A mean proportion of 0.157 was therefore estimated and applied to the skate landings for the period 1971 to 1990. Estimated Winter Skate landings were highest in 1974 and 1975 at around 20 t, declining slightly before peaking again at 10 t in 1981 and then declining to <500 kg annually up to 1990 (Fig. 28; Appendix 2).

Winter Skate discard amounts estimated directly using the fisheries observer data generally declined over the 1991 to 2014 period, from 170 t in 1991 and 312 t in 1992, to less than five tonnes annually since 2008 (Fig. 26; Table 9). Uncertainty in those estimates, which includes uncertainty in the discarded amount and the species composition of discards, is relatively high. Winter Skate discards in the sentinel fishery were considerably smaller than those in the commercial fishery, and have generally been 10 kg or less since 2005 (Table 9).

Most estimated Winter Skate discards originated in the coastal flatfish mobile-gear fishery; generally around 50% of the discards during the 1990s, rising to over 80% in the 2010s (Fig. 29). The offshore mobile-gear fishery has consistently produced 10 to 20% of estimated Winter Skate discards in almost all years, and the cod fisheries produced up to 40% of the discards in a number of years prior to 2003.

The bootstrapped distributions of the fishing mortality proportionality coefficient $b_S$ (equation 13) had modes of around 0.0009, 0.011 and 0.0004 for the cod, coastal flatfish and offshore flatfish fisheries, respectively (Fig. 30). It makes sense that the coastal flatfish fishery would have a much higher estimated value of $b_S$ given the considerable spatial overlap between this fishery and the distribution of Winter Skate. The estimated values of $b_S$ resulted in a very good correspondence between Winter Skate discards estimated using the observer data and those predicted using equaiton 13 for the cod fishery for the 1991 to 2014 period, and good correspondence for the two other fisheries (Fig. 30). Overall, estimated Winter Skate discards in the cod fisheries averaged around 300 t up to the mid-1970s, declining to an average around 100 t through the 1980s and early 1990s, and then rapidly declining to generally less than 5 t annually in the following years (Fig. 30). Estimated annual discards in the coastal flatfish fishery varied around an average of about 175 t from the 1970s to the early 1990s, declining gradually thereafter. Estimated annual discards in the offshore flatfish fishery varied around an average of 30 t from the 1970s to the early 1990s, also declining gradually thereafter.

Fixed-gear fisheries other than those directed at cod produced an average of 7.7% (95% confidence interval: 2.9 to 16.2%) of estimated Winter Skate discards for the 1991 to 2000 time period, and a lower proportion since then (Fig. 31). Mobile-gear fisheries other than the three main fisheries produced an average of 0.5% (0.1 to 1.6%) of the discards for the 1991 to 2000 time period, followed by a slightly higher proportion thereafter. The mean proportions for the 1991 to 2000 time period were used in analyses to estimate total Winter Skate discards for the 1971 to 1990 time period as described in section 6.1.2.2.

Estimated total Winter Skate discards for the entire 1971 to 2014 time period are presented in Figure 32 and Appendix 2 for both the original estimates derived from preliminary assumptions for Winter Skate natural mortality, and updated estimates derived using natural mortality values estimated as part of preliminary population modelling. The two series differ only for the 1971 to 1990 time period for which discards were estimated using the modified Baranov equation (equation 13). The trends in the two series are the same and are characterized by an elevated level during the early 1970s, a moderate level to 1992, followed by a large initial and subsequent gradual decline over time. The updated estimates were higher than the original estimates for 1971 to 1976, varying around 600 to 700 t annually compared to 500 to 600 t (Fig. 32; Appendix 2). The two series are quite similar thereafter, varying around 300 t from 1977 to the early 1990s. As reported above, the estimated discards then declined to between 10 and 50 t annually during the 1990s and early 2000s, and to lower levels thereafter.

Estimated survival of Winter Skate discarded in sGSL mobile gear fisheries covered by at-sea observers was lowest in 1991, at around 60%, varied around 85% during 1992 to 2006 and was closer to 95% thereafter (Fig. 33). It should be noted that these estimates are likely biased high as they do not account for possible enhanced predation mortality on discarded skates (Benoît et al. 2012). Estimated discard survival was lowest in the cod mobile gear fishery and similar in the two flatfish fisheries (Fig. 34). These values were used to estimate discard survival prior to 1991, as explained in section 6.1.2.3. Based on equations 14 and 15, an overall Winter Skate discard mortality of around 25% to 35% was estimated for most of the 1971 to 2001 time period (Fig 35; Appendix 2). Estimated discard mortality rates declined during the 2000s to around 5%. This decline reflects a higher proportion of Winter Skate discards originating from fisheries that are predicted to involve conditions that are favorable for survival such as lower handling times due to smaller catch amounts. As noted above, it is likely that the discard mortality estimates presented here are biased low, though the degree of bias is presently unknown. Furthermore, there is presently no information available to estimate any mortality related to the escape of Winter Skate from fishing gear.

Note that final estimates of landing, discards and discard mortality rates for the scallop, groundfish and shrimp fisheries are summarized in Appendix 2.

## 7. POPULATION MODELLING

Three types of population models were examined:

- stage-structured state-space models, the type of model used in the previous RPA of this species (Swain et al. 2006b),
- an age-structured length-based model which models population dynamics more realistically, and
- a surplus production model, in order to derive recovery targets.

### 7.1 STAGE-STRUCTURED STATE-SPACE MODELS

Earlier work used stage-structured models to take advantage of the length-composition information in the RV survey data despite the absence of aging data. The survey data were divided into two stages, representing juveniles (21 to 41 cm TL) and adults (≥ 42 cm TL). These models were state-space models implemented using a Bayesian approach. State-space models consist of two coupled components, a process model and an observation model. The process model describes the unobservable stochastic processes governing the population's dynamics, while the observation model describes the relationship between the unobserved states and the survey data that are observed with error. The Bayesian approach facilitates the incorporation of prior information on process and observation model parameters for which the data are uninformative and deals naturally with lognormal process variability and observation errors.

These models estimated time-varying total mortality with no separation into fishing and natural mortality. The advantage of these models is that there is no need to scale abundance to an absolute level. Instead, the model fits to relative abundance indices, which describe how abundance varies over time without determining its absolute level. Population dynamics were modelled as follows:

$$N_{1,t} = \left(N_{1,t-1}\,(1-\theta) + \tfrac{1}{2}\left(rN_{2,t-a}\right)\right) e^{-Z_{1,t}}\, e^{\eta_{1,t}} \qquad (16)$$

$$N_{2,t} = \left(N_{2,t-1} + N_{1,t-1}\,\theta\right) e^{-Z_{2,t}}\, e^{\eta_{2,t}}$$

where $N_{i,t}$ is abundance of stage $i$ (1 = juveniles; 2 = adults) in year $t$, $\theta$ is the transition probability from the juvenile to the adult stage, $r$ is the recruitment rate to the juvenile stage, $a$ is the number of years between the laying of egg cases and recruitment to the juvenile stage, $Z_{i,t}$ is the instantaneous rate of total mortality for stage $i$ in year $t$, and $\eta_{i,t}$ is an independent normal random variable with mean 0 and variance $\sigma_i^2$, representing process stochasticity in the dynamics at stage *i*. Recruitment to the juvenile stage was assumed to occur at an age of two years (see Fig. 1), following 6 to 9 months of incubation in egg cases and 15 to 18 months as free-swimming juveniles. Sex ratio was assumed to be 1:1. *Z* was allowed to differ between six time periods, each spanning 7 years (1971 to 2005) or 9 years (2006 to -2014). This model is unrealistic in one important respect. Juveniles move to the adult stage with probability θ instead of ageing within the juvenile stage and moving to the adult stage at the age of maturity. A model with more realistic dynamics is examined below.

The true abundance of each life stage ($N_{i,t}$) is not observed directly, rather survey catch rates provide observations of relative abundance $y_{i,t}$ with some error. Survey catch rates can be related to $N_{i,t}$ with the following observation model:

$$y_{i,t} = q_i \, N_{i,t} \, e^{\varepsilon_{i,t}} \qquad (17)$$

where $q_i$ is the catchability coefficient of stage *i* that scales the relative abundance index to $N_{i,t}$ (*i* = 1, 2) and $\varepsilon_{i,t}$ are independent normal random variables with mean 0 and variance $\tau_i^2$, representing observation error in the abundance index for stage *i*.

Because of the limited information available to the model, survey data were pre-processed to account for size selectivity of the survey trawl. This was done using the research-trawl selectivity curve estimated by Harley and Myers (2001) for flatfish. Flatfish were chosen as the fish group most closely resembling skates in body shape among the species having selectivity parameters estimated by Harley and Myers (2001). Small and large individuals were adjusted to the same relative catchability, but not to 100% catchability.

Vague priors were used for $Z_{i,t}$, $\sigma_i$ , and $\tau_i$ , except that the coefficients of variation (CV) of the survey data were used as lower limits for the priors for $\tau_i$ . Informative priors were used for other parameters. Priors for $\theta$ and *r* were based on life history information. Priors for initial population sizes (adults in 1969 and 1970, and juveniles in 1970) were based on the average survey catch rates in the early to mid-1970s. The prior for $q_2$ was centered on 1 because model abundance remained at the scale of relative abundance. The prior for $q_1$ was centered on 0.7 because of the lower availability of juveniles to the survey (Swain et al. 2006a). Priors are given in Table 10 and their calculation is described in more detail in Appendix 3.

Two *Z* models were examined. Model Z1 was based on the September RV indices alone. Zero values for both the juvenile and the adult indices in 2013 and 2014 were replaced by one-half the minimum non-zero index for each stage. The zero value for juveniles in 1977 was omitted from model fitting. Model Z2 used indices which combined the NS and RV data (like those in Fig. 17c and 19c). The construction of these indices is described in Appendix 4.

Models were implemented in WinBUGS (Version 1.4.3; Lunn et al. 2000). This software uses Gibbs sampling (Gelman et al. 2005), a Markov Chain Monte Carlo (MCMC) approach, to estimate the joint posterior distribution of the model parameters. A total of 225,000 samples was generated in each of two chains, the first 150,000 were discarded as a "burn-in," and every 30th sample thereafter was retained to reduce autocorrelation, yielding 5,000 samples from the joint posterior. We selected contrasting values within the range specified by each of the prior distributions to initialize the two chains.

### 7.1.1 Model Z1

This model was based solely on the September RV data and assumed that availability of Winter Skate to this survey did not change over time. This model provided a good fit to the juvenile and adult abundance indices (Fig. 36). Estimated juvenile abundance was very low in 1971. It increased from then to the mid-1980s but has been in decline since then. The rate of decline appeared to accelerate in the late 2000s, and juvenile abundance was at the lowest estimated level in 2013 and 2014 (when no juveniles were observed in the standard survey strata). Estimated adult abundance was at the highest level observed in the early 1970s but has declined steadily since then. The decline rate appeared to accelerate in the mid-2000s, and adult abundance was at the lowest estimated level in 2013 and 2014 (when no adults were observed in the standard survey strata).

The estimated rate of total mortality (*Z)* changed in opposite directions for juveniles versus adults over the 44-year time series (Fig. 37). Estimated juvenile mortality was very high in the early to mid-1970s ($Z$ = 2.70, 93% annually), declining to 69% annually during 1985 to 1991. It then gradually increased to 80% annually ($Z$ = 1.62) in recent years. In contrast, estimated adult mortality was relatively low in the early to mid-1970s ($Z$ = 0.18, 16% annually), increasing to 54% annually during 1985 to 1991. It has remained high since then, with the recent estimate at 63% annually ($Z$ = 0.99). No trends in process error are evident (Fig. 38), indicating that model structure is adequate to account for the main features in the dynamics of this population. Thus, the on-going decline in Winter Skate abundance appears to reflect an elevated and unsustainable level of adult mortality.

### 7.1.2 Model Z2

Inputs to this model accounted for density-dependent habitat selection, incorporating abundance indices for the RV survey and observed and predicted indices for the Northumberland Strait (NS), assuming that the density-dependent distribution conformed to the Ideal Free Distribution (Fig. 17). Indices were at the scale of trawlable abundance, with September RV indices adjusted to be equivalent to those in the Northumberland Strait survey (i.e., multiplied by 6). Because the NS survey accounts for the bulk of Winter Skate outside of the RV survey area, the prior for $q_1$ (juvenile catchability) was centred on 1, not on 0.7 like in model Z1.

Model predictions again fit the juvenile and adult abundance indices well (Fig. 39). The main difference between models Z1 and Z2 was that the accelerated rates of juvenile and adult decline evident in recent years based on Model Z1 were not evident in the data or results in model Z2. The recent acceleration in the decline evident in model Z1 presumably reflected decreased availability to the RV survey as Winter Skate distribution contracted into the preferred habitat in the Northumberland Strait (accounted for in model Z2). Patterns in $Z$ estimated by model Z2 were similar to those estimated by Z1 (Fig. 40). The main differences were that the changes in estimated Z were not as great in model Z2, particularly for adults. In model Z2, estimated adult $Z$ increased from 0.14% annually ($Z$ = 0.15) during 1971 to 1977 to 48% ($Z$ = 0.64) during 1985 to 1991, with the estimate for the most recent period at 45% ($Z$ = 0.60). Again there were no trends in process error (Fig. 41), indicating that model structure adequately accounts for the population dynamics.

## 7.2 AGE-STRUCTURED MODEL

### 7.2.1 Methods

The population dynamics assumed in this model are described by the following equations:

$$N_{i+1,y+1} = N_{i,y} e^{-(F_{i,y} + M_{i,y})} \tag{18}$$

$$C_{i,y} = \frac{F_{i,y}}{F_{i,y} + M_{i,y}} N_{i,y} \left(1 - e^{-(F_{i,y} + M_{i,y})}\right) \tag{19}$$

$$N_{2,y} = r_{y-2}\, A_{y-2}/2 \tag{20}$$

$$r_y = e^{R_a + rdev_y} \tag{21}$$

where $N_{i,y}$ is population abundance at age *i* in year *y*, $F_{i,y}$ and $M_{i,y}$ are the instantaneous rates of fishing and natural mortality, respectively, at age *i* in year *y*, and $C_{i,y}$ is the fishery removal in numbers at age *i* in year *y*. Model ages *i* were 2 years to 9+ years (9 years and older). Years spanned 1971 to 2014. *M* was estimated separately for six time blocks (7-year blocks between 1971 and 2005 and a final 9-year block) and two age groups (2 to 4 years and 6 to 9+). *M* of 5-year olds was assumed to be the average of *M* for ages 2 to 4 and ages 6 to 9+ in the same year. Fishery removals ($C_y$) consisted of landings and discarded catch that did not survive:

$$C_y = L_y + m_S D_{S,y} + m_{G,y} D_{G,y} \tag{22}$$

where $C_y$ is total fishery removals in tonnes in year *y*, $L_y$ is the landed catch in year *y*, $D_{S,y}$ and $D_{G,y}$ are the discarded catch in the scallop and groundfish fisheries respectively, and $m_S$ and $m_{G,y}$ are discard mortality (the fraction dying) in the scallop and groundfish fisheries. Abundance at ages 2 to 9+ in 1971 and age 2 in 1972 were parameters (on the log scale) estimated by the model. Abundance at age 2 in other years was obtained from equation 20 where *A* is adult abundance and *r* is the recruitment rate (age-2 recruits per female spawner). A 1:1 sex ratio was assumed. Given 50% maturity at age 5, *A* was the sum of abundances at ages 6 to 9+ years plus half the age-5 abundance. The recruitment rate *r* in year *y* was calculated based on an average log recruitment rate $R_a$ and an annual deviate (equation 21). The recruitment rate deviate was assumed to be normally distributed with a mean of 0 and standard deviation of 0.2. Age and year effects on *F* were assumed to be separable:

$$F_{i,y} = s_i F_y \tag{23}$$

where $F_y$ is fully recruited *F* in year *y* and $s_i$ is fishery selectivity for age *i*.

Data inputs included (Table 11):

- total annual landings, discards in the scallop fishery and discards in groundfish fisheries, all in tonnes;
- annual variation in discard mortality rate in groundfish fisheries (input as a ratio of the mean rate);
- mean weight of individuals in the catch by year and length group (juveniles 21-41 cm, and adults ≥ 42 cm);
- proportion of the fishery catch (in numbers) by length group in each year;
- survey abundance index by length group and year, and
- mean weight of individuals in the survey abundance indices by length group and year.

The survey abundance indices accounted for density-dependent habitat selection and were the same as the indices used for the model Z2 (Appendix 4), except that there was no adjustment for size-selectivity of the survey trawl. Proportions of the fishery catch by length group and mean individual weights in the catch by length group were obtained as described in Appendix 5.

Parameters estimated in the model include log abundance at ages 2 to 9+ in 1971 and age 2 in 1972, average log recruitment rate, annual recruitment rate deviations (1973 to 2012), log *M* for juveniles and adults in six time periods, fishery and survey selectivity parameters (two each), fully recruited survey catchability, log observation error variances for the juvenile and adult abundance indices, and log discard mortality rates (two parameters). Prior distributions were provided for the following parameters: abundance at age in 1971 and for age 2 in 1972, average recruitment rate, recruitment rate deviations, adult and juvenile *M* in 1971 to 1976, survey catchability, and discard mortality (Appendix 6).

Two sensitivity runs were also conducted. In the first run, the 95th percentile for the estimates of landings and discards were used instead of the median estimate. The second run used greater values for the priors for discard mortality. For discards in fisheries for groundfish, the 95th percentile of estimated discard mortality was used as the prior mean. The point estimate of discard mortality in the scallop fishery was multiplied by 1.87 (the average ratio of the 95th percentile and median estimates of discard mortality in fisheries for groundfish).

Models were implemented using AD Model Builder (Fournier et al. 2011) and fit using penalized maximum likelihood. Uncertainty was incorporated based on 210,000 MCMC samples, with the first 10,000 samples discarded as a "burn-in" period and every 40th subsequent sample retained to reduce autocorrelation, yielding a sample of 5,000 iterations from the joint posterior distribution of the parameters and derived variables.

### 7.2.2 Results

The base model fit the juvenile and adult abundance indices well (Fig. 42), with no substantial patterns in the residuals (Fig. 43). The predicted size composition of the fishery catch (i.e. the proportions of juveniles and adults) fit the main trends in the "observed" (i.e., independently estimated) proportions (Fig. 44). The estimated fishery selectivity-at-age and survey catchability-at-age appeared reasonable (Fig. 45).

Estimated juvenile abundance fluctuated around a relatively high value (56 million) in the 1970s and 1980s (Fig. 46a). Juvenile abundance progressively declined beginning in the late 1980s, reaching the lowest level on record in 2014 (estimated to be 3 million, 5.6% of the mean level in the 1970s and 1980s). Juvenile biomass trends showed a similar pattern (Fig. 46b). Adult abundance was at a high level in the 1970s, with estimated abundance averaging 7.7 million during this period (Fig. 46c). Adult abundance has been in decline since the late 1970s, with the 2014 level estimated to be the lowest on record at 0.2 million individuals, 3% of the average level in the 1970s. Adult biomass showed a similar temporal pattern, with the 2014 biomass estimated to be the lowest on record at 199 t, 2% of the average estimated level in the 1970s (Fig. 46d).

The estimated recruitment rate fluctuated without any long-term pattern for the 1971 to 2012 cohorts (Fig. 47). The average recruitment rate was estimated to be 10.4 recruits per female spawner, greater than the prior mean of 9 (Appendix 6 Fig. 1).

Temporal patterns in the natural mortality of juveniles appeared to be relatively minor (Fig. 48), with the median estimate fluctuating around an average value of 0.94 (i.e., an annual mortality of 61%). In contrast, there was a large change in estimated *M* of adults over time (Fig. 48), steadily increasing from a median estimate of 0.11 (10% annually) during 1971 to 1977 to 1.0 (63% annually) during 1992 to 1998. Estimated adult *M* has remained high since then, with the median estimate averaging 57% since 1999.

In contrast to *M*, the instantaneous rate of fishing mortality (*F*) appears to be negligible (Fig. 49). The estimated fishing mortality of juveniles (a weighted average of ages 2 to 4 years) was below 0.1% in all years, below 0.05% in all but 8 years and averaged 0.006% over the last 5 years. Although higher for adults (a weighted average of ages 6 years and older), estimated fishing mortality averaged only 1.8% from 1971 to 1993 (when the cod fishery was first closed), 0.9% from 1994 to 2000, 0.3% during 2001 to 2010 and 0.1% since 2011.

Increasing estimated catch from the median estimate to its 95th percentile increased estimated *F* by a factor of 1.8 on average (Fig. 50). However, *F* remained very low in all years even at the higher catch level. For juveniles, *F* varied between 0.0003 and 0.002 (mean 0007, 0.07% annually) in the 1971 to 2000 time period, declining to an average of 0.0002 during 2001 to 2010 and 0.00008 during 2011 to 2014. For adults, *F* varied between 0.009 and 0.05 (mean 0.027, 2.7% annually) in the 1971 to 2000 time period, declining to an average of 0.006 during 2001 to 2010 and 0.0025 during 2011 to 2014. Because *F* remained very low, these increases in *F* did not result in perceptible changes in estimated *M* (Fig. 51) or abundance (Fig. 52).

The increases in discard mortality rate resulted in slightly lower increases in *F*, by average factors of 1.4 for juveniles and 1.5 for adults (Fig. 50). Nonetheless, these changes in *F* were associated with slight changes in estimated *M* in some periods (both slight increases and decreases; Fig. 51), as well as changes in estimated abundance (Fig. 52). However, general conclusions about changes in abundance and the roles played by *M* and *F* in the changes in stock status were robust to these changes in the levels of catch or discard mortality.

Fishery catch normally plays an important role in establishing the scale of population abundance in stock assessment models. However, in this case, fishing mortality was too low throughout the assessment time series to be very informative about the scale of abundance. Instead, this scale was determined largely by the priors on recruitment rate, survey catchability (*q*) and abundances at age in 1971 and at age 2 in 1972. Models with different priors for *q* and starting abundance at age were also examined. The abundance scale differed in these models, particularly for juveniles, but conclusions about population status and changes in productivity (i.e., adult *M*) were very similar (see Appendix 7).

## 7.3 SURPLUS PRODUCTION MODEL

A surplus production model was used to obtain an estimate of $B_{MSY}$, the biomass producing maximum sustainable yield (MSY). A limit reference point (LRP) of 40% of $B_{MSY}$ is proposed as the abundance recovery objective for this stock.

### 7.3.1 Methods

The model is a state-space Schaefer production model incorporating both observation error (in the survey) and process error in the population dynamics. Only the adult portion of the population was modelled in order to obtain a reference point relevant to adult biomass and because the scaling of juvenile abundance was very uncertain. Data inputs were the adult biomass index scaled to "rockhopper" catchability, estimates of landings and discards in the scallop and groundfish fisheries, and an index of temporal changes in the mortality of discards in groundfish fisheries (i.e., the ratio of the annual mortality rate to the average rate). The adult biomass index was constructed in a manner analogous to the adult abundance index described in Figure 19. The model for the population dynamics is:

$$B_{t+1} = \left(B_t + B_t r_t \left(1 - {}^{B_t}/_{K}\right) - C_t\right) e^{\eta_t} \qquad (24)$$

where $B_t$ is population biomass in year *t*, $C_t$ is the fishery removal in year *t*, $r_t$ is the intrinsic rate of population increase in year *t*, *K* is carrying capacity and the $\eta_t$ are independent random variables with mean 0 and variance $\sigma^2$, representing stochasticity in the population dynamics. The parameter *r* was allowed to vary between six time blocks (7-year blocks or a final 9-year block).

Fisheries removals were calculated as:

$$C_t = (L_t + Dm_S * Ds_t + \delta_t * Dm_G * Dg_t) * \rho_t \qquad (25)$$

where $L_t$ is landings in year t, $Ds_t$ and $Dg_t$ are discards in year t from the shrimp and groundfish fisheries, respectively, $Dm_S$ is the discard mortality rate in the shrimp fishery, $Dm_G$ is the average rate of mortality of discards from fisheries for groundfish, $\delta_t$ is the ratio of the annual to the average discard mortality rate in fisheries for groundfish, and $\rho_t$ is the proportion of removals in year *t* that are adults. The estimates from the base age-structured model were used for $\rho_t$.

The observation model was:

$$y_t = qB_t e^{\varepsilon_t} \tag{26}$$

where $y_t$ is the survey biomass index in year *t*, *q* is catchability of Winter Skate to the survey scaled as "rockhopper" equivalents, and the $\varepsilon_t$ are independent normal random variables with mean 0 and variance $\tau^2$, representing observation error in the survey biomass index.

Informative priors were used for the following parameters:

- Catchability *q* was assumed to be lognormally distributed with a mean of $\log_e(0.725)$ and a standard deviation (SD) of 0.05.
- The prior distributions for the rates of discard mortality in the fisheries for shrimp and groundfish were the same as those used in the age-structured model (Appendix 6).
- Following McAllister et al. (2001), an informative prior was developed for *r* during the 1970 to 1976 time period. This was based on the growth model described above, the length-weight relationship in the 1970s based on July survey data, and information on recruitment rate, maturity at age and natural mortality by length group. The resulting prior for *r* during 1970 to 1976 was normally distributed with a mean of 0.052 and SD = 0.02.
- The prior for population biomass in 1970 ($B_0$) was estimated based on the average biomass index during 1971 to 1975 divided by 0.725 (the prior mean for survey *q*). This prior was lognormally distributed with a mean of $\log_e(6.976085)$ and SD = 0.15. (The scale of this index is thousand tonnes.)

Vague priors were used for the remaining parameters:

- A uniform prior between -0.8 and 0.25 was used for *r* in other periods.
- A uniform prior between 2 and 6 was used for $\log_e(K)$.
- A uniform prior between 0.05 and 1 was used for $\sigma$.
- A uniform prior between 0.35 and 1 was used for $\tau$. The lower limit was based on the CV of the September survey data.

Posteriors were estimated using 275,000 iterations of 2 chains, with the first 200,000 discarded as a burn-in period and with every 30th of the remaining iterations saved to reduce autocorrelation, resulting in 5,000 samples of the posterior distribution (2,500 samples for each chain).

In addition to $B_t$, $y_t$, and the parameters above, posterior distributions of the following quantities were calculated from the model parameters outputs:

- Annual exploitation rate; $C_t / B_t$
- Biomass at maximum sustainable yield; $B_{MSY} = K / 2$
- Maximum surplus production; $C_{MSY} = rK / 4$
- Conservation limit reference point (LRP); $Blim = 0.4 * B_{MSY}$. This choice is based on the policy on the Precautionary Approach and is proposed as the abundance recovery target.
- The exploitation rate at MSY; $E_{MSY}$.

### 7.3.2 Results

The surplus production model provided a good fit to the survey index (Fig. 53). There were no serious patterns in either the observation or process errors. The posterior distribution for *q* changed little from its informative prior distribution (Fig. 54). In contrast, the posterior distribution for $B_0$ shifted to a higher value relative to its informative prior. The posterior for *K* changed substantially from its uniform prior. Its posterior distribution was highly skewed to the right (as is typical for this parameter), but most of the density was concentrated at low values, with a median estimate of 22.7 thousand tons. Variables derived from *K* ($B_{MSY}$, Blim) had similarly shaped posterior distributions. The median estimates of $B_{MSY}$ and the LRP (Blim) were 11.37 kt and 4.549 kt, respectively.

Estimated adult biomass was stable throughout most of the 1970s at values near 7,000 t, but has been in decline since the late 1970s (Fig. 55). Biomass in 2014 is estimated to be 86 t, a 99% decline from the levels in the 1970s. The probability that adult biomass was below the LRP increased from about 40% in the 1970s to 100% since about 1995.

The decline in adult biomass since the late 1970s reflects a decline in productivity. The exploitation rate is estimated to have been low and declining throughout the 44-year time series, declining from an average level of 0.03 in the early 1970s to 0.013 throughout the 1980s and 1990s (Fig. 56). It has declined further since then to 0.0035 in the 2000s and 0.0020 since 2010. Since estimated exploitation rate has been in decline, the decline in productivity appears to reflect natural factors. The estimated intrinsic rate of increase (*r*) was very low but positive in the early 1970s (Figs. 57 and 58). However, in periods since then, the posterior distributions of *r* mostly spanned negative values, with median values in the range from -0.16 to -0.06. The median in the most recent period is -0.16.

The LRP estimated by this model is 0.6481 of the biomass in 1971. Using this proportion, adult biomass estimated by the age-structured model was compared to this proxy for the LRP (Fig. 59). The probability that biomass was below the LRP was about 0 in the 1970s increasing to 100% since about 1995.

## 7.4 PROJECTIONS

The population was projected forward using the surplus production and age-structured models under various assumptions about future productivity. These projections propagated uncertainty in the model estimates. Using the surplus production model, the population was projected forward 25 years assuming that productivity remained at the level of the 2006 to 2014 time period, with fishery removals set to 0. Under current productivity conditions, the population is projected to continue to decline even with no fishery removals (Fig. 60). The probability that adult biomass is below 100 t, already high at 68% in 2014, exceeded 95% by 2034 (Fig. 61). At the end of the projection in 2039, the probabilities that adult biomass would be below 10 t and 2 t at current productivity levels were 83% and 60%, respectively. These very low biomass levels could be considered proxies for extinction, indicating that based on this model there is a substantial probability of extinction of this DU within 25 years under current productivity levels, even with no fishery removals.

Using the age-structured model, the population was projected forward 50 years assuming current productivity conditions and at various lower levels of adult *M*. In initial projections, fishery removals were assumed to be nil. Under current conditions, the population is expected to continue to decline rapidly (Fig. 62). There is a 95% probability that the population will be below 50 t by 2030, below 10 t by 2042 and below 2 t by 2054 (Fig. 63). It is almost certain that this population will be extinct by mid-century at the current level of adult natural mortality, even with no fishery removals. This assumes no changes in juvenile natural mortality or average recruitment rates. Both these components of productivity have shown no trend over time according to this model.

If adult M were reduced to 40% of its current level, the population would be expected to continue to decline at a slow rate. At the end of the 50-year projection, there is a 78% probability that adult biomass would be less than 50 t, a 30% probability that it would be below 10 t, and a 5% probability that it would be below 2 t. Thus, even with no fishery removals, the population would be expected to decline to extinction; it just would take longer.

If adult M were reduced to 20% of its current level, adult biomass would be expected to slowly increase. The median estimate of biomass at the end of the 50-yr projection is 565 t, about three times the 2014 estimate but only 5% of the 1971 level. The probability that biomass would reach the LRP in 50 years is estimated to be 1%.

A reduction in adult M to 15% of its current level would result in a relatively rapid increase in adult biomass (Fig. 62d). The probability that biomass would reach the LRP in 50 years is estimated to be 7%. The median estimate of adult biomass in 50 years is 1,556 t, about 8 times the 2014 level and 14% of the 1971 level.

At its low values and the current high values of natural mortality, fishing mortality has a negligible impact on the population trajectory (Fig. 64). During 2011 to 2014, *F* for ages 6+ and ages 1 to 4 years averaged 0.001 and 0.00004, respectively. In projections assuming current values for other components of productivity, the adult biomass trajectory using these values of *F* is indistinguishable from that assuming no fishery removals (Fig. 64). The result is the same using the slightly higher values of *F* during 2001 to 2010, 0.003 and 0.0001 for adults and juveniles, respectively (Fig. 64).

# 8. HABITAT ASSOCIATIONS

## 8.1 METHODS

We examined the summertime associations of Winter Skate catches (numbers) with depth and bottom temperature in the RV and NS surveys. While the RV survey data allow for an examination of long-term changes in habitat associations, these data are not appropriate for characterizing the habitat preferences of Winter Skate in the sGSL because the survey excludes much of the Northumberland Strait, as well as many areas with depths <20 m, which are important areas for Winter Skate in summer. Conversely, while the NS survey provides a better coverage of potential Winter Skate habitat, the relatively short history of that survey precludes examination of long-term changes in habitat associations.

Habitat associations were examined using the distribution-functions approach of Perry and Smith (1994). Associations were examined separately for juveniles and adults for four decadal blocks (1975 to 1984, 1985 to 1994, 1995 to 2004, and 2005 to 2014) and for strata 415 to 439 (1975 to 2014) and 401 to 439 (1985 to 2014) for the RV survey data. For the NS survey, habitat associations for juveniles and adults were examined based on all pertinent years. Of the 1,375 pertinent NS survey tows, 248 had missing bottom temperature values. Because missing temperature values were essentially random with respect to depth (Fig. 65), these missing values were simply dropped from the analysis, rather than trying to impute a value.

Habitat associations for juveniles and adults in the NS survey were also examined using generalized additive models (GAMs; Wood 2006). This was also attempted for the data from the RV survey but not pursued due to a very high degree of zero-inflation in the data. The models for the NS survey data were of the form:

$$Y_i \sim NB(\mu_i, k) \tag{27}$$

$$\mathrm{E}[Y_i] = \mu_i = \exp(\beta_0 + s(X_i) + Z_i) \tag{28}$$

$$\mathrm{var}[Y_i] = \mu_i + \mu_i^2/k \tag{29}$$

where $Y_i$ is the catch of skates in tow i, $s(X_i)$ is a cubic spline function of the habitat variable, $Z_i$ is an offset term to account for the distance towed in tow *i* with respect to a standard 0.625 NM tow, and *k* is the dispersion parameter of the negative binomial distribution. We specified the degree of smoothing for the habitat term by setting its degrees of freedom to a maximum of 5, though the optimal degree of smoothing was estimated by generalized crossed-validation.

## 8.2 RESULTS

### 8.2.1 Depth associations

The annual RV survey covers almost all areas with depth ≥20 m in the sGSL, including the slope of the Laurentian channel. The survey area is dominated by depths between 25 and 125 m, but includes depths as shallow as 15 m and deeper than 350 m (Fig. 66). Juvenile Winter Skate preferred depths <50 m in the survey and were found only at depths <100 m, with a few exceptions (Fig. 66). Over the decades, juvenile Winter Skate increasingly became more concentrated at depths around 30 m, suggesting that these depths are preferred. Associations with depth were very comparable whether data from strata 415 to 439 or from strata 401 to 403 were considered. Like juveniles, adult Winter Skate also displayed a preference for depths <50 m, and a particular preference for depths around 30 m (Fig. 67). The preference for shallow depths also increased over the decades.

The NS survey area (strata 1 to 5) covers depths generally from 5 to 55 m, with the majority of the area covered by depths between 5 and 40 m (Fig. 68). In this area, both juvenile and adult Winter Skate most commonly occurred at depths between 10 and 20 m. Comparing the distribution of depths occupied by Winter Skate with that available in the survey area, Winter skate appeared to prefer depths of 10 to 20 m and avoid depths of 25 to 40 m. Predicted densities of both juvenile and adult Winter Skate were highest at depths <20 m, declining rapidly with increasing depth to zero by 50 m (Fig. 69). This result is consistent with the findings from the RV survey for the 2005 to 2014 period.

### 8.2.2 Bottom temperature associations

Most of the RV survey area is covered by bottom waters ≤ 5°C (Fig. 70), reflecting the large portion of the area that is comprised of the Magdalen Shallows, which are covered by the waters of the Cold Intermediate Layer. Across all decades, both juvenile and adult Winter Skate displayed a preference for bottom waters ≥ 6°C (Figs. 70 and 71). Preference for waters ≥ 10°C was perhaps slightly stronger, particularly for adults during the 2005 to 2014 period (Fig. 71).

The availability of areas associated with a given bottom temperature in the NS survey increased with temperature from around 0°C to 20°C, dropping off quickly to near zero availability for bottom temperatures of 22 °C (Fig. 72). Though both juvenile and adult Winter Skate occurred at temperatures > 5°C, they displayed a clear preference for temperatures between 15 and 20°C and neutral selection of areas above 20°C. Predicted densities of juveniles and adults increased with bottom water temperature, peaking at around 17 or 18 °C, then dropping with increasing temperature (Fig. 73).

Based on these results, it is very unlikely that warming of summer sea surface temperatures (and therefore coastal bottom temperatures) in the sGSL since the 1980s (Galbraith et al. 2015) have reduced the amount of habitat available to juvenile and adult Winter Skate. In fact, this warming may have increased the amount of available habitat based on the apparent temperature preferences.

# 9. THREATS, LIMITING FACTORS AND MITIGATION MEASURES

## 9.1 FISHERY REMOVALS

There is no directed fishery for Winter Skate in this DU. Based on estimates of bycatch in other fisheries and of discard mortality rates, fishing mortality has been very low since 1971, the earliest year with estimates (Fig. 49). The median estimate of fishing mortality for adults declined from about 3% in the 1970s to 0.07% in 2014. Sensitivity analyses based on the 95th percentiles of estimates of fishery removals or discard mortality rates also yield negligible fishery mortality rates, from 5% in the 1970s to 0.2% in 2014. Fishery removals do not appear to be an important cause of decline in abundance of skate in this DU.

## 9.2 EFFECTS OF FISHING ON WINTER SKATE HABITAT

Bottom-contacting mobile fishing gear can reduce habitat complexity, alter seafloor structure and alter the relative abundance of benthic species, favoring species with high turnover rates, among other effects (reviewed in Rice 2006). Winter Skate may be vulnerable to such effects given its benthivorous diet and possible habitat-specific requirements for the successful development of embryos in egg cases. The sGSL scallop (*Placopecten magellanicus*) fishery and certain mobile-gear groundfish fisheries occur in Winter Skate habitat and may have affected Winter Skate productivity, though fishing effort has declined considerably in all of these fisheries particularly since the mid to late 1990s. Any impacts are therefore likely to have been more pronounced in the past.

The possible short and long term impacts of scallop dredging on the coastal benthic community in the sGSL was studied in recent experiments conducted in Chaleur Bay and Northumberland Strait (LeBlanc et al. 2015). That study found little to no evidence for an effect of dredging on the benthic invertebrate community and concluded that broad scale seasonal changes in the abundance of benthic species were far greater than any local fishing effect. The authors argued that the nearshore demersal invertebrate communities in the sGSL are likely adapted to physical disturbance, including that caused by dredging, because these habitats are physically dynamic, being characterized by strong wave action and by occasional ice scouring in winter. The results of LeBlanc et al. (2015) suggest that any effect of scallop dredging on Winter Skate via food web alteration is therefore likely to be small at best. Because scallop dredges have generally been found to produce more pronounced changes in benthic communities compared to bottom trawls (e.g., Collie et al. 2000), similar bottom-up effects of mobile groundfish fishing are also expected to be small. Furthermore, following the arguments of LeBlanc et al. (2015), it is likely that Winter Skate early life stages are adapted to their dynamic coastal habitat and therefore less susceptible to the physical disturbance caused by fishing.

## 9.3 CLIMATE CHANGE

In summer and early fall, Winter Skate in the southern Gulf of St. Lawrence are largely confined to areas with depths less than 50 m. The average September bottom temperature in this area increased by about 2°C from the mid-1970s to the early 2000s (Fig. 74). It might be hypothesized that this increase in temperature may be harmful to Winter Skate, resulting in temperatures warmer than their preferred or optimal range. However, recent values of the bottom temperature index (averaging about 14°C; Fig. 74) are instead slightly cooler than their preferred range of 15 to 20°C (Fig. 72). Furthermore, as the abundance of Winter Skate declined, they became increasingly concentrated in the warmest waters available in the Northumberland Strait (Fig. 75). This confirms that the warmest waters available in summer remain within the preferred temperature range of sGSL Winter Skate, suggesting that the effects of climate change are not yet deleterious to the skate in this DU and do not provide a direct explanation for the increases in the natural mortality of adults in this population.

## 9.4 PREDATION BY GREY SEAL

The 2005 recovery potential assessment for sGSL Winter Skate identified elevated adult natural mortality (*M*) as the main demographic rate contributing to the DU's decline (Swain et al. 2006). Subsequently, Benoît et al (2011a) considered the weight of evidence for various hypotheses concerning the causes of the increased and high adult *M*. The hypotheses considered were:

- unaccounted fishing mortality that might be misinterpreted as *M*,
- condition-related mortality (i.e., starvation),
- life history changes that may be linked to changes in *M*,
- predation by Grey Seal, and
- predation by other predators.

The strongest available evidence suggested that predation by Grey Seal appeared to be the largest contributor to high *M*. Among the evidence cited was the steep rise over time in the number of Grey Seal that occur in the sGSL (Fig. 76; Hammill et al. 2014a), which would be consistent with a predator pit effect on Winter Skate *M*, and which also corresponds with increases in adult *M* for numerous other large demeral fish species in the sGSL (Benoît and Swain 2011; Swain and Benoît 2015). The high degree of spatial overlap in the summer distributions of Winter Skate and Grey Seal appeared to make Winter Skate particularly vulnerable to predation by seals. The only other hypothesis with some evidence was that *M* may have increased temporarily during a period of low condition in the mid-1990s, but that poor condition cannot explain currently high levels of *M* for adult Winter Skate.

New information published since the review of Benoît et al (2011a) further supports the Grey Seal predation hypothesis as a major cause of increased adult *M* in sGSL Winter Skate. Benoît et al (2011b) used a simulation model that included the spatio-temporal overlap between sGSL Winter Skate and Grey Seal, along with a bioenergetics model for Grey Seal prey consumption, to assess whether predation by Grey Seal could plausibly explain elevated *M* in adult Winter Skate. The authors found that predation by Grey Seal could explain all of adult Winter Skate *M* even if Winter Skate comprise no more than 0.6% of the diet of the Grey Seal that overlap spatially with them, and no more than 0.2% of the average Grey Seal diet. Though skates have not been found in recent seal diet sampling in the sGSL (Hammill et al. 2007, 2014b), this is likely due to their low current abundance in the area and their lack of hard body parts that can be recovered from seal digestive tracts. At less than 1% of the diet, Winter Skate would be a rare prey item and would be highly unlikely to be recovered during diet sampling. Sampling prior to the 1990s, when skates were more abundant, found skates in approximately 30% of the seal stomachs examined in the sGSL and skates were considered a regular diet item (Benoit and Bowen 1990). More recently, Winter Skate were found to represent 0.5% of the mean Northwest Atlantic Grey Seal diet (range 0 to 2%, depending on sex and season), as inferred using quantitative fatty acid signature analysis (QFASA; Beck et al. 2007). Though the reliability of QFASA is uncertain (Nordstrom et al. 2008; Rosen and Tollit 2012), if these values are accurate, they are clearly sufficient to explain most or all of the increase in adult Winter Skate *M*.

Interannual changes in the distribution of grey seals from July to October have recently been estimated by Swain et al. (2015). The estimates were derived from a combination of satellite telemetry of seal movements of about 200 individuals and changes across decades in the distribution of seals among haul-out locations in the sGSL (details in Swain et al. 2015). Over time the presence of Grey Seal has particularly intensified in the Shediac Valley, at the eastern and western ends of the Northumberland Strait and between the Magdalen Islands and Prince Edward Island (Fig. 77). The areas in and west of the Northumberland Strait were historically important areas for Winter Skate in the summer (Benoît et al. 2003). The summer distribution of Winter Skate is now concentrated near Bedeque Bay (PEI) (Fig. 77, bottom right panel), which is in a small region where predation risk appears to be low (Fig. 77, bottom left). The contraction of the Winter Skate distribution into this area may therefore reflect both a density-dependent reduction in distribution and an attempt to minimize the risk of predation. These mechanisms, particularly risk of predation, also appear to underlie long term changes in the distributions of adult Atlantic Cod, White Hake and Thorny Skate in the sGSL (Swain et al. 2015).

## 10. SUMMARY

Winter Skate in the southern Gulf of St. Lawrence are distinct from those occurring elsewhere in the Northwest Atlantic, maturing at a much smaller size (40 to 42 versus 75 cm) and a much younger age (5 years versus 11 to 13 years). Winter Skate occur very rarely in the northern Gulf of St. Lawrence, and those that do occur there appear to be of the typical, late-maturing type. Thus, the sGSL should be retained as a separate DU of Winter Skate, distinct from Winter Skate in other areas including the nGSL. Reported occurrences of Winter Skate in the St. Lawrence Estuary are rare (three individuals in 1953 and one in 1988). One of these individuals was confirmed to be of the early-maturing sGSL type. However, their rarity in the Estuary suggests that this area may be outside of the normal range of the sGSL type of Winter Skate.

As predicted in the 2005 RPA (Swain et al. 2006a, 2006b), biomass and abundance of sGSL Winter Skate has continued to decline. Based on catch rates in the September RV survey, biomass and adult abundance have both declined by 99% since the early 1980s. No mature Winter Skate were captured in the standard RV survey strata in 2013 and 2014, the first times on record. The preferred habitats of Winter Skate are better surveyed by the August Northumberland Strait survey. The biomass index from this survey has declined by 78% since the start of the survey in 2000.

The geographic range of catch rates of adults in the RV survey declined from 6,500 km$^2$ in the mid-1980s to 377 km$^2$ in 2012 (no adults were caught in the standard survey strata in 2013 and 2014). Distribution also contracted in the Northumberland Strait survey, with catches of adults restricted to a very small area of stratum 3 in the central strait in 2014. Catches of recruits are also mostly confined to stratum 3.This area appears to be the only important refuge remaining for Winter Skate in the sGSL.

There has been no directed fishery for Winter Skate in the sGSL. Skate landings were highest in 1974 and 1975 at about 130 t, declining to one tonne or less in years since the mid-2000s. Estimated discards of Winter Skate in the scallop fishery declined from over 100 t in 1971 to 1972 to about one tonne annually since 2005. The mortality of discards from the scallop fishery is thought to be very low, about 10%. Estimated discards in fisheries for groundfish were 600 to 700 t annually in the early 1970s, declining to less than 5 t annually since 2008. Estimated mortality rates of discards from these fisheries were 25% to 35% annually during the 1971 to 2001 time period, declining to less than 10% since 2007.

Three types of models were used to examine the population dynamics of Winter Skate: a stage-structured model, an age-structured model and a surplus production model. Results were generally consistent among the three types of models. Based on the surplus production model, adult biomass declined from 7,000 t in the 1970s to 86 t in 2014, well below the estimated LRP of 4,550 t (40% of $B_{MSY}$). Based on the age-structured model, adult biomass declined from an average of about 11,000 t in the 1970s to 199 t in 2014, a 98% decline. Estimated abundance declined from 7.7 million in the 1970s to 0.2 million in 2014 for adults, and from an average of 50.7 million to 3 million for juveniles. No trend was evident in the rate of recruitment. For both the age-structured and surplus production models, the probability that the population was below the LRP was estimated to be 100% since 1995.

Fishing mortality appeared to be negligible. For adults, it was estimated to be 3% in the early 1970s, declining to 0.6% during 2001 to 2010 and 0.25% since 2011. For juveniles, estimated fishing mortality averaged 0.07% annually during 1971 to 2000, declining to <0.01% since 2011.

Estimated natural mortality of adults increased from 10% annually during 1971 to 1977 to 63% annually during 1992 to 1998, averaging 57% annually since 1999. No trend in the natural mortality of juveniles was evident, with the median estimate fluctuating around 61% annually. The large decline in abundance of Winter Skate in this DU appears to be due to the large increase in the natural mortality of adult skates. Increased predation by Grey Seal appears to be an important cause of the current high adult natural mortality.

Under current productivity conditions, the population is projected to continue to decline and is almost certain to be extinct by mid-century, even with no fishery removals. The recent very low levels of fishing mortality have negligible impact on the population trajectory at current levels of other components of productivity (in particular adult $M$). With no fishing, population biomass would be expected to increase slowly if adult natural mortality were decreased by 80% and relatively rapidly if decreased by 85%.

## 11. ACKNOWLEDGEMENTS

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# TABLES

*Table 1. Abundance indices for adult Winter Skate (≥ 42 cm total length TL) in the Northumberland Strait (NS) and September RV surveys. Indices are shown for two groups of strata for each survey at the scales of stratified mean fish per standard tow and trawlable abundance (TA) in thousands. The number of trawlable units is given for each group of strata.*

| | RV 415-439 (1729346 units) | | RV 401-439 (1787248.5 units) | | NS 3,5 (384703.6 units) | | NS 1-3,5 (630648.4 units) | |
|---|---|---|---|---|---|---|---|---|
| Year | fish/tow | TA (1000s) | fish/tow | (TA 1000s) | fish/tow | (TA 1000s) | fish/tow | (TA 1000s) |
| 1971 | 0.4234 | 732.12 | | | | | | |
| 1972 | 0.2216 | 383.17 | | | | | | |
| 1973 | 0.4040 | 698.63 | | | | | | |
| 1974 | 0.2822 | 488.09 | | | | | | |
| 1975 | 0.3213 | 555.71 | | | | | | |
| 1976 | 0.4194 | 725.21 | | | | | | |
| 1977 | 0.1143 | 197.60 | | | | | | |
| 1978 | 0.5094 | 880.91 | | | | | | |
| 1979 | 0.3242 | 560.57 | | | | | | |
| 1980 | 0.3345 | 578.53 | | | | | | |
| 1981 | 0.1957 | 338.38 | | | | | | |
| 1982 | 0.3004 | 519.56 | | | | | | |
| 1983 | 0.1682 | 290.81 | | | | | | |
| 1984 | 0.1195 | 206.68 | 0.1156 | 206.68 | | | | |
| 1985 | 0.1187 | 205.26 | 0.1198 | 214.05 | | | | |
| 1986 | 0.2334 | 403.62 | 0.2389 | 427.05 | | | | |
| 1987 | 0.1292 | 223.45 | 0.1389 | 248.31 | | | | |
| 1988 | 0.1341 | 231.88 | 0.1369 | 244.73 | | | | |
| 1989 | 0.1041 | 180.04 | 0.1212 | 216.57 | | | | |
| 1990 | 0.0569 | 98.33 | 0.0586 | 104.67 | | | | |
| 1991 | 0.1068 | 184.72 | 0.1213 | 216.85 | | | | |
| 1992 | 0.0697 | 120.51 | 0.0680 | 121.51 | | | | |
| 1993 | 0.1077 | 186.23 | 0.1042 | 186.23 | | | | |
| 1994 | 0.0195 | 33.81 | 0.0189 | 33.81 | | | | |
| 1995 | 0.0177 | 30.65 | 0.0276 | 49.29 | | | | |
| 1996 | 0.0265 | 45.89 | 0.0294 | 52.58 | | | | |
| 1997 | 0.0423 | 73.22 | 0.0415 | 74.24 | | | | |
| 1998 | 0.0286 | 49.51 | 0.0290 | 51.81 | | | | |
| 1999 | 0.0139 | 24.02 | 0.0279 | 49.89 | | | | |
| 2000 | 0.0325 | 56.16 | 0.0402 | 71.82 | | | | |
| 2001 | 0.0358 | 61.93 | 0.0347 | 61.93 | | | | |
| 2002 | 0.0169 | 29.26 | 0.0168 | 30.05 | | | | |
| 2003 | 0.0179 | 31.01 | 0.0174 | 31.01 | 0.3797 | 146.06 | 0.2963 | 186.88 |
| 2004 | 0.0063 | 10.82 | 0.0067 | 11.94 | 0.3128 | 120.33 | 0.2110 | 133.10 |
| 2005 | 0.0068 | 11.81 | 0.0087 | 15.50 | 0.1568 | 60.31 | 0.2583 | 162.88 |
| 2006 | 0.0188 | 32.49 | 0.0182 | 32.49 | 0.4652 | 178.95 | 0.3442 | 217.07 |
| 2007 | 0.0125 | 21.69 | 0.0129 | 23.09 | 0.6902 | 265.52 | 0.4692 | 295.90 |
| 2008 | 0.0199 | 34.37 | 0.0192 | 34.37 | 0.5438 | 209.22 | 0.3678 | 231.96 |
| 2009 | 0.0027 | 4.63 | 0.0040 | 7.16 | 0.1473 | 56.66 | 0.0898 | 56.66 |
| 2010 | 0.0088 | 15.22 | 0.0085 | 15.22 | | | | |
| 2011 | 0.0003 | 0.55 | 0.0010 | 1.73 | | | | |
| 2012 | 0.0066 | 11.49 | 0.0075 | 13.32 | 0.3898 | 149.95 | 0.2378 | 149.95 |
| 2013 | 0.0000 | 0.00 | 0.0000 | 0.00 | 0.1551 | 59.67 | 0.1136 | 71.65 |
| 2014 | 0.0000 | 0.00 | 0.0006 | 1.16 | 0.1413 | 54.38 | 0.0862 | 54.38 |

*Table 2. Abundance indices for juvenile Winter Skate (21-41 cm TL) in the Northumberland Strait (NS) and September RV surveys. Indices are shown for two groups of strata for each survey at the scales of stratified mean fish per standard tow and trawlable abundance (TA) in thousands. The number of trawlable units is given for each group of strata.*

| | RV 415-439 (1729346 units) | | RV 401-439 (1787248.5 units) | | NS 3,5 (384703.6 units) | | NS 1-3,5 (630648.4 units) | |
|---|---|---|---|---|---|---|---|---|
| Year | fish/tow | TA (1000s) | fish/tow | (TA 1000s) | fish/tow | (TA 1000s) | fish/tow | (TA 1000s) |
| 1971 | 0.0092 | 15.95 | | | | | | |
| 1972 | 0.0235 | 40.67 | | | | | | |
| 1973 | 0.0444 | 76.85 | | | | | | |
| 1974 | 0.0298 | 51.51 | | | | | | |
| 1975 | 0.2158 | 373.18 | | | | | | |
| 1976 | 0.0865 | 149.67 | | | | | | |
| 1977 | 0.0000 | 0.00 | | | | | | |
| 1978 | 0.0913 | 157.92 | | | | | | |
| 1979 | 0.0592 | 102.40 | | | | | | |
| 1980 | 0.0332 | 57.45 | | | | | | |
| 1981 | 0.0698 | 120.73 | | | | | | |
| 1982 | 0.1171 | 202.46 | | | | | | |
| 1983 | 0.2022 | 349.74 | | | | | | |
| 1984 | 0.0828 | 143.12 | 0.0848 | 151.50 | | | | |
| 1985 | 0.2068 | 357.68 | 0.2051 | 366.59 | | | | |
| 1986 | 0.1205 | 208.43 | 0.1169 | 208.93 | | | | |
| 1987 | 0.0773 | 133.64 | 0.0831 | 148.61 | | | | |
| 1988 | 0.1415 | 244.63 | 0.1369 | 244.63 | | | | |
| 1989 | 0.0962 | 166.36 | 0.1219 | 217.79 | | | | |
| 1990 | 0.0471 | 81.53 | 0.0517 | 92.46 | | | | |
| 1991 | 0.0404 | 69.93 | 0.0478 | 85.50 | | | | |
| 1992 | 0.0446 | 77.10 | 0.0434 | 77.50 | | | | |
| 1993 | 0.0281 | 48.56 | 0.0276 | 49.24 | | | | |
| 1994 | 0.0029 | 5.00 | 0.0036 | 6.39 | | | | |
| 1995 | 0.0410 | 70.97 | 0.0652 | 116.60 | | | | |
| 1996 | 0.0521 | 90.13 | 0.0571 | 102.00 | | | | |
| 1997 | 0.0496 | 85.76 | 0.0578 | 103.22 | | | | |
| 1998 | 0.0237 | 40.92 | 0.0264 | 47.16 | | | | |
| 1999 | 0.0207 | 35.82 | 0.0350 | 62.59 | | | | |
| 2000 | 0.0501 | 86.65 | 0.0495 | 88.44 | | | | |
| 2001 | 0.0179 | 30.99 | 0.0173 | 30.99 | | | | |
| 2002 | 0.0084 | 14.50 | 0.0288 | 51.53 | | | | |
| 2003 | 0.0086 | 14.83 | 0.0083 | 14.83 | 0.2494 | 95.96 | 0.2596 | 163.70 |
| 2004 | 0.0117 | 20.22 | 0.0115 | 20.47 | 0.1793 | 68.99 | 0.1804 | 113.76 |
| 2005 | 0.0007 | 1.15 | 0.0030 | 5.34 | 0.3092 | 118.97 | 0.5604 | 353.40 |
| 2006 | 0.0133 | 23.05 | 0.0130 | 23.31 | 0.5624 | 216.37 | 0.4177 | 263.43 |
| 2007 | 0.0045 | 7.76 | 0.0048 | 8.65 | 1.0236 | 393.79 | 0.9864 | 622.06 |
| 2008 | 0.0069 | 11.87 | 0.0066 | 11.87 | 0.8834 | 339.86 | 0.6068 | 382.70 |
| 2009 | 0.0208 | 35.95 | 0.0201 | 35.95 | 0.2130 | 81.96 | 0.1522 | 95.98 |
| 2010 | 0.0033 | 5.68 | 0.0032 | 5.68 | | | | |
| 2011 | 0.0006 | 1.02 | 0.0006 | 1.02 | | | | |
| 2012 | 0.0030 | 5.14 | 0.0078 | 13.95 | 0.2110 | 81.16 | 0.1432 | 90.30 |
| 2013 | 0.0000 | 0.00 | 0.0003 | 0.52 | 0.2593 | 99.75 | 0.1756 | 110.75 |
| 2014 | 0.0000 | 0.00 | 0.0005 | 0.83 | 0.1801 | 69.29 | 0.1099 | 69.29 |

*Table 3. The number of tows (A including tows catching no Winter Skate; B excluding tows with no Winter Skate) available by year, stratum, and survey to test for difference in fishing efficiency for Winter Skate (all sizes combined) between the Northumberland Strait (NS) and September RV surveys. For the RV survey, tows were available in 2000 to 2002 in 432 and in 2000 to 2004 and 2007 in stratum 433 but were excluded due to an absence of tows in these strata in the NS survey.*

| Year | Strata 402 RV and 5 NS | | Strata 432 RV and 6 NS | | Strata 433 RV and 7,9,10 NS | |
|---|---|---|---|---|---|---|
| | RV | NS | RV[1] | NS | RV[1] | NS |
| A) including tows with no Winter Skate | | | | | | |
| 2000 | 3 | 22 | 0 | 0 | 0 | 0 |
| 2001 | 1 | 31 | 0 | 0 | 0 | 0 |
| 2002 | 3 | 7 | 0 | 0 | 0 | 0 |
| 2003 | 1 | 34 | 2 | 32 | 0 | 0 |
| 2004 | 5 | 35 | 8 | 6 | 0 | 0 |
| 2005 | 2 | 37 | 4 | 32 | 13 | 81 |
| 2006 | 3 | 40 | 4 | 49 | 10 | 16 |
| 2007 | 3 | 37 | 4 | 37 | 0 | 0 |
| 2008 | 3 | 37 | 4 | 40 | 11 | 27 |
| 2009 | 3 | 36 | 4 | 35 | 9 | 45 |
| 2012 | 3 | 13 | 3 | 19 | 8 | 28 |
| 2013 | 3 | 14 | 3 | 18 | 9 | 31 |
| 2014 | 3 | 14 | 3 | 21 | 9 | 27 |
| Total | 36 | 357 | 39 | 289 | 69 | 255 |
| B) excluding tows with no Winter Skate | | | | | | |
| 2000 | 1 | 2 | 0 | 0 | 0 | 0 |
| 2001 | 0 | 2 | 0 | 0 | 0 | 0 |
| 2002 | 1 | 1 | 0 | 0 | 0 | 0 |
| 2003 | 0 | 0 | 1 | 1 | 0 | 0 |
| 2004 | 2 | 0 | 3 | 0 | 0 | 0 |
| 2005 | 0 | 1 | 0 | 1 | 0 | 3 |
| 2006 | 0 | 3 | 0 | 2 | 1 | 1 |
| 2007 | 0 | 5 | 0 | 2 | 0 | 0 |
| 2008 | 0 | 2 | 1 | 0 | 1 | 0 |
| 2009 | 0 | 1 | 0 | 2 | 0 | 0 |
| 2012 | 0 | 0 | 1 | 0 | 0 | 1 |
| 2013 | 1 | 1 | 0 | 0 | 0 | 0 |
| 2014 | 1 | 0 | 0 | 0 | 0 | 0 |
| Total | 6 | 18 | 6 | 8 | 2 | 5 |

*Table 4. Effects of survey (RV, NS), year and stratum on catch rates of Winter Skate in the eastern Northumberland Strait.*

| Parameter | Estimate | SE | t value | P (2-sided) |
|---|---|---|---|---|
| Intercept | -4.5380 | 1.572 | -2.887 | 0.004 |
| Survey 2 (NS) | 2.0167 | 1.288 | 1.566 | 0.118 |
| year 2001 | 0.8060 | 1.073 | 0.751 | 0.453 |
| year 2002 | 1.8675 | 1.132 | 1.650 | 0.099 |
| year 2003 | -1.6670 | 1.749 | -0.953 | 0.341 |
| year 2004 | -3.0386 | 3.380 | -0.899 | 0.369 |
| year 2005 | 0.2412 | 1.057 | 0.228 | 0.819 |
| year 2006 | 0.4714 | 1.037 | 0.455 | 0.649 |
| year 2007 | 1.2909 | 0.995 | 1.298 | 0.195 |
| year 2008 | -0.2192 | 1.126 | -0.195 | 0.846 |
| year 2009 | -0.1332 | 1.108 | -0.120 | 0.904 |
| year 2012 | -1.0407 | 1.609 | -0.647 | 0.518 |
| year 2013 | -0.3588 | 1.314 | -0.273 | 0.785 |
| year 2014 | -3.5957 | 4.616 | -0.779 | 0.436 |
| stratum 432 | -0.8728 | 0.440 | -1.984 | 0.048 |
| stratum 433 | -0.8967 | 0.567 | -1.581 | 0.114 |

*Table 5. Statistics for the regression of log density of Winter Skate in the Northumberland Strait (strata 3 and 5) against log density in the RV survey area (strata 415 to 439). $\beta_0$ and $\beta_1$ are the regression intercept and slope respectively, SE their standard error and P their significance level. $R^2$ is the proportion of variation in log density in the Northumberland Strait accounted for by the regression on log density in the RV survey area, and df is the error degrees of freedom.*

| Parameter | Total biomass | Adult abundance | Juvenile abundance |
|---|---|---|---|
| $\beta_0$ | 1.2248 | 1.0164 | -0.8540 |
| SE($\beta_0$) | 0.5204 | 0.5262 | 1.3433 |
| $P(\beta_0)$ | 0.038 | 0.090 | 0.54 |
| $\beta_1$ | 0.5644 | 0.4932 | 0.0624 |
| SE($\beta_1$) | 0.1335 | 0.1105 | 0.2763 |
| $P(\beta_1)$ | 0.0014 | 0.0021 | 0.83 |
| $R^2$ | 0.62 | 0.71 | 0.006 |
| df | 11 | 8 | 8 |

*Table 6. Commercial fisheries (identified by number) included in the estimation of skate bycatch. Fisheries are defined by target species and gear class, either fixed (F) or mobile gear (M). Also provided is the year in which a 100% dockside monitoring program (DMP) was introduced to each fishery, and a summary of the pooling of observer data required for the analysis for the fisheries and years with inadequate observations. No pooling across years was employed for a given fishery for years not listed here. The directed White Hake fishery has been under moratorium since 1995.*

| Target species | Gear class | DMP | Years requiring pooled data | Pooled years |
|---|---|---|---|---|
| Atlantic Cod (*Gadus morhua*) | F | 1994 | 1991 | 1991-1993 |
| | | | 1993-1997 | 1991-1999 |
| | M | before 1991 | - | - |
| Redfish (*Sebastes* spp.) | M | before 1991 | 1998-2006 | 1991-2006 |
| | | | 2006-2008; 2010-2014 | 2007-2014 |
| Atlantic Halibut (*Hippoglossus hippoglossus*) | F | 1997 | 1991-1993; 1996; 1997 | 1991-1999 |
| Greenland Halibut (*Reinhardtius hippoglossoides*) | F | 1997 | 1992 | 1991-1994 |
| White Hake (*Urophycis tenuis*) | F&M | 1995 | 1991-1995 | 1991-1995 |
| American Plaice (*Hippoglossoides platessoides*) | F | 2003 | 1991-1993; 1998-2007; 2012 | 1991-2014 |
| A. Plaice and Witch Flounder (*Glyptocephalus cynoglossus*) | M | 1994 | - | - |
| Winter Flounder (*Pseudopleuronectes americanus*) | F | 2003 | 1991-1998 | 1991-1998 |
| | | | 1999-2006 | 1999-2006 |
| | | | 2007-2014 | 2007-2014 |
| | M | 1998 | 2006-2014 | 2000-2014 |
| Yellowtail Flounder (*Limanda ferruginea*) | M | 2002 | 1991-1998 | 1995-1998 |
| | | | 1999-2002 | 2000-2005 |
| Spiny Dogfish (*Squalus acanthias*) | F | 1994 | 1991; 1992 | 1993-1995 |
| | | | 2000-2006 | 1998-2006 |
| Northern Shrimp (*Pandalus borealis*) | M | 1991 | - | - |

*Table 7. Summary for the sGSL of the annual total number of fishing trips and trips covered by fishery observers in groundfish and shrimp fisheries. In addition to the total number of observed trips, the table also provides the number of trips for which discarded skates and retained skates were reported.*

| Year | Total fishing trips | Observed trips | | |
|---|---|---|---|---|
| | | Total | Reporting discarded skates | Reporting retained skates |
| 1991 | 19,689 | 416 | 249 | 8 |
| 1992 | 16,929 | 324 | 242 | 3 |
| 1993 | 12,041 | 207 | 180 | 19 |
| 1994 | 9,056 | 307 | 211 | 17 |
| 1995 | 5,539 | 259 | 172 | 29 |
| 1996 | 4,544 | 213 | 129 | 14 |
| 1997 | 5,766 | 174 | 128 | 14 |
| 1998 | 4,975 | 238 | 180 | 12 |
| 1999 | 7,835 | 238 | 145 | 10 |
| 2000 | 7,668 | 377 | 213 | 16 |
| 2001 | 6,214 | 330 | 145 | 6 |
| 2002 | 5,427 | 306 | 161 | 12 |
| 2003 | 3,353 | 249 | 168 | 24 |
| 2004 | 4,775 | 390 | 183 | 24 |
| 2005 | 4,679 | 336 | 158 | 12 |
| 2006 | 4,044 | 267 | 141 | 6 |
| 2007 | 2,928 | 160 | 90 | 9 |
| 2008 | 2,803 | 148 | 89 | 2 |
| 2009 | 2,646 | 125 | 89 | 3 |
| 2010 | 3,828 | 125 | 74 | 4 |
| 2011 | 3,203 | 109 | 62 | 5 |
| 2012 | 3,008 | 146 | 93 | 8 |
| 2013 | 2,451 | 141 | 83 | 3 |
| 2014 | 2,490 | 188 | 80 | 4 |

*Table 8. Official skate landings for 1971 to 2014 in the sGSL and landings estimated using at-sea observer records, for all skate species combined and for Winter Skate specifically, 1991 to 2014. Estimates of Winter Skate landings are presented as initial estimates, based only on observer reports, and estimates adjusted for reported landings, with 95% confidence intervals presented for the latter (LCI- lower confidence interval, UCI- upper). All values are in tonnes.*

| | | Estimated (all skates) | | | Estimated (Winter Skate) | | | |
|---|---|---|---|---|---|---|---|---|
| Year | Landings | Mean | LCI | UCI | Initial | Adjusted | LCI | UCI |
| 1971 | 8.00 | | | | | | | |
| 1972 | 2.00 | | | | | | | |
| 1973 | 3.00 | | | | | | | |
| 1974 | 132.00 | | | | | | | |
| 1975 | 131.00 | | | | | | | |
| 1976 | 43.00 | | | | | | | |
| 1977 | 5.00 | | | | | | | |
| 1978 | 12.00 | | | | | | | |
| 1979 | 17.00 | | | | | | | |
| 1980 | 22.00 | | | | | | | |
| 1981 | 66.00 | | | | | | | |
| 1982 | 1.00 | | | | | | | |
| 1983 | 35.00 | | | | | | | |
| 1984 | 0.00 | | | | | | | |
| 1985 | 0.00 | | | | | | | |
| 1986 | 3.00 | | | | | | | |
| 1987 | 0.00 | | | | | | | |
| 1988 | 1.00 | | | | | | | |
| 1989 | 1.00 | | | | | | | |
| 1990 | 0.68 | | | | | | | |
| 1991 | 4.19 | 14.40 | 4.58 | 34.25 | 4.51 | 1.31 | 0.22 | 1.90 |
| 1992 | 1.66 | 10.76 | 3.13 | 25.43 | 3.64 | 0.56 | 0.10 | 0.78 |
| 1993 | 7.98 | 6.13 | 2.48 | 13.01 | 1.91 | 2.48 | 0.94 | 3.51 |
| 1994 | 55.83 | 154.73 | 5.98 | 380.08 | 2.82 | 1.02 | 0.16 | 13.12 |
| 1995 | 32.74 | 27.87 | 13.08 | 51.60 | 6.52 | 7.66 | 4.11 | 12.18 |
| 1996 | 24.36 | 46.44 | 5.76 | 103.15 | 1.61 | 0.84 | 0.08 | 7.42 |
| 1997 | 9.55 | 22.85 | 5.39 | 51.54 | 4.90 | 2.05 | 0.21 | 6.71 |
| 1998 | 8.04 | 11.31 | 2.04 | 28.49 | 0.81 | 0.58 | 0.06 | 3.74 |
| 1999 | 11.17 | 14.06 | 2.90 | 26.28 | 0.50 | 0.40 | 0.01 | 1.86 |
| 2000 | 5.68 | 17.02 | 1.59 | 65.61 | 10.23 | 3.42 | 0.61 | 3.75 |
| 2001 | 3.61 | 3.33 | 0.48 | 6.27 | 0.61 | 0.66 | 0.01 | 2.60 |
| 2002 | 6.25 | 2.37 | 0.80 | 3.73 | 0.54 | 1.43 | 0.03 | 3.68 |
| 2003 | 9.86 | 14.36 | 6.20 | 25.53 | 0.02 | 0.01 | 0.00 | 0.00 |
| 2004 | 21.02 | 25.23 | 7.26 | 48.86 | 0.38 | 0.32 | 0.00 | 1.45 |
| 2005 | 13.88 | 5.32 | 1.15 | 12.16 | 0.08 | 0.21 | 0.00 | 1.04 |
| 2006 | 2.82 | 2.86 | 0.48 | 6.13 | 0.14 | 0.14 | 0.00 | 0.73 |
| 2007 | 1.85 | 12.86 | 0.62 | 32.81 | 0.30 | 0.04 | 0.00 | 0.52 |
| 2008 | 1.92 | 2.41 | 0.68 | 4.02 | 0.35 | 0.28 | 0.00 | 0.77 |
| 2009 | 5.32 | 1.57 | 0.11 | 3.60 | 0.34 | 1.16 | 0.00 | 3.60 |
| 2010 | 3.27 | 2.19 | 0.52 | 3.71 | 0.69 | 1.03 | 0.16 | 1.83 |
| 2011 | 2.53 | 3.40 | 1.11 | 5.73 | 0.46 | 0.34 | 0.00 | 0.88 |
| 2012 | 1.36 | 2.99 | 1.16 | 4.45 | 0.46 | 0.21 | 0.03 | 0.46 |
| 2013 | 0.64 | 0.99 | 0.17 | 1.35 | 0.06 | 0.04 | 0.00 | 0.00 |
| 2014 | 0.20 | 1.36 | 0.40 | 1.84 | 0.08 | 0.01 | 0.00 | 0.02 |

*Table 9. Discard amounts (t) for Winter Skate observed in the sGSL Sentinel fisheries and estimated for sGSL commercial fisheries, based on at-sea observer data. LCI and UCI are respectively the lower and upper 95% confidence intervals for the estimated commercial fishery discards. All values are in tonnes.*

| Year | Sentinel | Commercial | LCI | UCI |
|---|---|---|---|---|
| 1991 | | 169.67 | 68.76 | 308.09 |
| 1992 | | 311.78 | 190.00 | 513.26 |
| 1993 | | 48.67 | 28.85 | 77.02 |
| 1994 | | 29.98 | 15.37 | 48.99 |
| 1995 | | 28.99 | 14.59 | 62.46 |
| 1996 | 1.08 | 17.26 | 9.39 | 25.05 |
| 1997 | 0.99 | 84.27 | 37.16 | 236.58 |
| 1998 | 0.9 | 13.17 | 8.23 | 20.06 |
| 1999 | 0.41 | 30.33 | 15.51 | 49.73 |
| 2000 | 0.61 | 29.10 | 19.80 | 40.65 |
| 2001 | 0.33 | 16.03 | 11.16 | 21.87 |
| 2002 | 0.22 | 9.53 | 6.38 | 13.17 |
| 2003 | 0.09 | 6.25 | 3.32 | 9.64 |
| 2004 | 0.08 | 7.37 | 5.26 | 10.00 |
| 2005 | 0.01 | 2.23 | 1.02 | 3.89 |
| 2006 | 0.01 | 17.45 | 6.17 | 38.32 |
| 2007 | 0.01 | 6.82 | 4.22 | 9.35 |
| 2008 | 0.01 | 4.13 | 2.27 | 7.26 |
| 2009 | 0.01 | 3.45 | 1.32 | 7.99 |
| 2010 | 0.01 | 2.72 | 1.75 | 3.91 |
| 2011 | 0.01 | 3.29 | 1.72 | 5.69 |
| 2012 | 0.04 | 2.43 | 1.51 | 3.80 |
| 2013 | 0 | 1.63 | 1.05 | 2.34 |
| 2014 | 0 | 0.56 | 0.19 | 1.14 |

*Table 10. Prior distributions used for parameters of the stage-structured state-space population models for Winter Skate in the southern Gulf of St. Lawrence. The second parameter of the lognormal distribution is given as precision ($1/\sigma^2$). The notation I (x,y) indicates that distributions are truncated at x and y so that values must be greater than x and less than y.*

| Parameter | Model Z1 | Model Z2 |
|---|---|---|
| θ | beta(28.57, 71.43)\|(0.15,0.40) | beta(28.57, 71.43)\|(0.15,0.40) |
| $Z_1$ | normal(2.5,0.01)\|(0,5) | normal(2.5,0.01)\|(0,5) |
| $Z_2$ | normal(1.5,0.01)\|(0,3) | normal(1.5,0.01)\|(0,3) |
| $r$ | lognormal(2.197, 6.667)\| (0.01,1000) | lognormal(2.197, 6.667)\| (0.01,1000) |
| $\sigma_1$ | uniform(0,2) | uniform(0,2) |
| $\sigma_2$ | uniform(0,1) | uniform(0,1) |
| $N_{1,1970}$ | lognormal(-0.8696, 10) | lognormal(1.6410, 16) |
| $N_{2,1970}$ | lognormal(-0.8696, 10) | lognormal(1.6410, 16) |
| $N_{2,1969}$ | lognormal(-1.3326, 6.25) | lognormal(1.0622, 16) |
| $q_1$ | lognormal(-0.3567, 20) | lognormal(0, 20) |
| $q_2$ | lognormal(0, 35) | lognormal(0, 35) |
| $\tau_1$ | uniform(0.50,2) | uniform(0.50,2) |
| $\tau_2$ | uniform(0.36,1) | uniform(0.36,1) |

*Table 11. Data inputs for the age-structured population models for Winter Skate in the southern Gulf of St. Lawrence. Note: L is landings in tonnes, $d_S$ and $d_G$ are discards from the scallop and groundfish fisheries, respectively, in tonnes, Urel is annual discard mortality rate in groundfish fisheries relative to the 1971 to 2014 mean, $Cw_J$ and $Cw_A$ are mean individual weights (kg) of juveniles and adults, respectively, in the catch, $Pg_J$ and $Pg_A$ are the proportions of the catch composed of juveniles and adults respectively, $I_J$ and $I_A$ are the abundance indices for juveniles and adults in trawlable abundance (1000s of fish), and $Iw_J$ and $Iw_A$ are mean individual weights (kg) of juveniles and adults in the population.*

| Year | L (t) | $d_S$ (t) | $d_G$ (t) | Urel | $Cw_J$ | $Cw_A$ | $Pg_J$ | $Pg_A$ | $I_J$ | $I_A$ | $Iw_J$ | $Iw_A$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1971 | 1.26 | 178.78 | 599.90 | 1.51 | 0.481 | 1.307 | 0.043 | 0.957 | 123.27 | 5272.42 | 0.486 | 1.326 |
| 1972 | 0.31 | 147.98 | 733.68 | 1.49 | 0.520 | 1.324 | 0.068 | 0.932 | 309.45 | 2938.26 | 0.478 | 1.352 |
| 1973 | 0.47 | 92.11 | 709.21 | 1.52 | 0.456 | 1.300 | 0.094 | 0.906 | 575.26 | 5051.41 | 0.521 | 1.309 |
| 1974 | 20.72 | 61.23 | 689.72 | 1.60 | 0.383 | 1.235 | 0.206 | 0.794 | 379.17 | 3648.82 | 0.319 | 1.157 |
| 1975 | 20.56 | 81.74 | 570.83 | 1.52 | 0.402 | 1.449 | 0.229 | 0.771 | 2699.49 | 4102.11 | 0.355 | 1.409 |
| 1976 | 6.75 | 100.10 | 782.44 | 1.37 | 0.378 | 1.401 | 0.244 | 0.756 | 1064.08 | 5226.84 | 0.406 | 1.414 |
| 1977 | 0.78 | 54.67 | 310.19 | 1.70 | 0.415 | 1.563 | 0.143 | 0.857 | NA | 1646.73 | 0.364 | 1.740 |
| 1978 | 1.88 | 62.33 | 252.21 | 1.49 | 0.412 | 1.563 | 0.116 | 0.884 | 1089.40 | 6249.21 | 0.438 | 1.596 |
| 1979 | 2.67 | 68.18 | 407.36 | 1.20 | 0.325 | 1.735 | 0.119 | 0.881 | 699.05 | 4134.59 | 0.257 | 1.506 |
| 1980 | 3.45 | 65.70 | 325.12 | 1.19 | 0.367 | 1.717 | 0.139 | 0.861 | 389.68 | 4254.46 | 0.314 | 1.873 |
| 1981 | 10.36 | 93.02 | 364.77 | 1.21 | 0.347 | 1.711 | 0.201 | 0.799 | 816.99 | 2631.49 | 0.389 | 1.614 |
| 1982 | 0.16 | 61.09 | 329.62 | 1.18 | 0.342 | 1.628 | 0.352 | 0.648 | 1371.30 | 3860.14 | 0.296 | 1.825 |
| 1983 | 5.49 | 87.01 | 372.44 | 1.13 | 0.334 | 1.379 | 0.387 | 0.613 | 2375.92 | 2302.80 | 0.331 | 1.102 |
| 1984 | 0.00 | 61.55 | 106.64 | 1.49 | 0.581 | 1.566 | 0.506 | 0.494 | 975.73 | 1711.53 | 0.355 | 1.287 |
| 1985 | 0.00 | 56.91 | 225.09 | 1.06 | 0.305 | 1.278 | 0.410 | 0.590 | 2445.89 | 1701.42 | 0.233 | 1.241 |
| 1986 | 0.47 | 52.37 | 312.94 | 1.00 | 0.320 | 1.442 | 0.390 | 0.610 | 1427.55 | 3077.57 | 0.313 | 1.409 |
| 1987 | 0.00 | 40.14 | 277.22 | 1.07 | 0.298 | 1.405 | 0.368 | 0.632 | 915.40 | 1830.67 | 0.247 | 1.465 |
| 1988 | 0.16 | 37.70 | 239.52 | 1.08 | 0.321 | 1.461 | 0.421 | 0.579 | 1674.00 | 1890.29 | 0.293 | 1.411 |
| 1989 | 0.16 | 44.09 | 262.06 | 1.08 | 0.345 | 1.296 | 0.462 | 0.538 | 1137.13 | 1520.68 | 0.319 | 1.372 |
| 1990 | 0.11 | 34.43 | 222.42 | 1.18 | 0.362 | 1.164 | 0.368 | 0.632 | 557.18 | 916.84 | 0.327 | 1.115 |
| 1991 | 1.31 | 32.19 | 169.67 | 1.91 | 0.367 | 1.059 | 0.346 | 0.654 | 478.84 | 1554.35 | 0.385 | 1.061 |
| 1992 | 0.56 | 27.49 | 311.78 | 0.73 | 0.387 | 1.165 | 0.266 | 0.734 | 530.61 | 1084.39 | 0.391 | 0.959 |
| 1993 | 2.48 | 33.35 | 48.67 | 1.55 | 0.392 | 1.184 | 0.265 | 0.735 | 337.10 | 1565.20 | 0.372 | 1.309 |
| 1994 | 1.02 | 27.82 | 29.98 | 1.19 | 0.341 | 1.380 | 0.293 | 0.707 | 35.16 | 395.89 | 0.365 | 1.227 |
| 1995 | 7.66 | 25.44 | 28.99 | 0.63 | 0.260 | 1.288 | 0.540 | 0.460 | 507.98 | 367.84 | 0.267 | 1.335 |
| 1996 | 0.84 | 24.68 | 18.34 | 1.09 | 0.282 | 1.233 | 0.560 | 0.440 | 660.13 | 499.80 | 0.248 | 1.205 |
| 1997 | 2.05 | 20.46 | 85.26 | 0.50 | 0.269 | 1.063 | 0.499 | 0.501 | 646.50 | 721.94 | 0.253 | 1.070 |
| 1998 | 0.58 | 15.91 | 14.07 | 1.27 | 0.287 | 1.044 | 0.469 | 0.531 | 319.62 | 530.07 | 0.285 | 0.927 |
| 1999 | 0.40 | 10.16 | 30.74 | 1.73 | 0.294 | 1.089 | 0.525 | 0.475 | 291.91 | 307.21 | 0.203 | 1.298 |
| 2000 | 3.42 | 8.51 | 29.71 | 1.11 | 0.318 | 1.373 | 0.495 | 0.505 | 742.24 | 584.93 | 0.303 | 1.295 |
| 2001 | 0.66 | 4.91 | 16.36 | 1.16 | 0.333 | 1.407 | 0.454 | 0.546 | 281.12 | 631.81 | 0.385 | 1.447 |
| 2002 | 1.43 | 3.01 | 9.75 | 0.61 | 0.356 | 1.370 | 0.317 | 0.683 | 140.26 | 355.32 | 0.320 | 1.583 |
| 2003 | 0.01 | 2.58 | 6.34 | 0.75 | 0.322 | 1.146 | 0.390 | 0.610 | 184.93 | 332.12 | 0.275 | 0.841 |
| 2004 | 0.32 | 2.24 | 7.45 | 0.64 | 0.326 | 1.117 | 0.390 | 0.610 | 190.32 | 185.24 | 0.365 | 0.977 |
| 2005 | 0.21 | 1.68 | 2.24 | 0.64 | 0.302 | 1.216 | 0.406 | 0.594 | 125.89 | 131.19 | 0.279 | 1.870 |
| 2006 | 0.14 | 1.21 | 17.46 | 0.84 | 0.304 | 1.132 | 0.284 | 0.716 | 354.65 | 373.87 | 0.223 | 0.949 |
| 2007 | 0.04 | 1.43 | 6.83 | 0.24 | 0.285 | 0.960 | 0.279 | 0.721 | 440.38 | 395.68 | 0.449 | 0.981 |
| 2008 | 0.28 | 1.09 | 4.14 | 0.12 | 0.301 | 0.923 | 0.449 | 0.551 | 411.06 | 415.41 | 0.226 | 0.940 |
| 2009 | 1.16 | 1.16 | 3.46 | 0.28 | 0.283 | 0.962 | 0.466 | 0.534 | 297.64 | 84.41 | 0.284 | 0.709 |
| 2010 | 1.03 | 0.80 | 2.73 | 0.21 | 0.302 | 1.111 | 0.657 | 0.343 | 103.28 | 221.56 | 0.365 | 1.251 |
| 2011 | 0.34 | 0.92 | 3.30 | 0.13 | 0.364 | 1.259 | 0.299 | 0.701 | 20.05 | 65.31 | 0.313 | 0.670 |
| 2012 | 0.21 | 0.88 | 2.47 | 0.31 | 0.347 | 1.230 | 0.333 | 0.667 | 112.02 | 218.90 | 0.238 | 1.190 |
| 2013 | 0.04 | 1.02 | 1.63 | 0.09 | 0.357 | 1.258 | 0.303 | 0.697 | 99.75 | 59.67 | 0.266 | 0.939 |
| 2014 | 0.01 | 0.99 | 0.56 | 0.22 | 0.357 | 1.258 | 0.303 | 0.697 | 69.29 | 54.38 | 0.519 | 0.875 |

## FIGURES

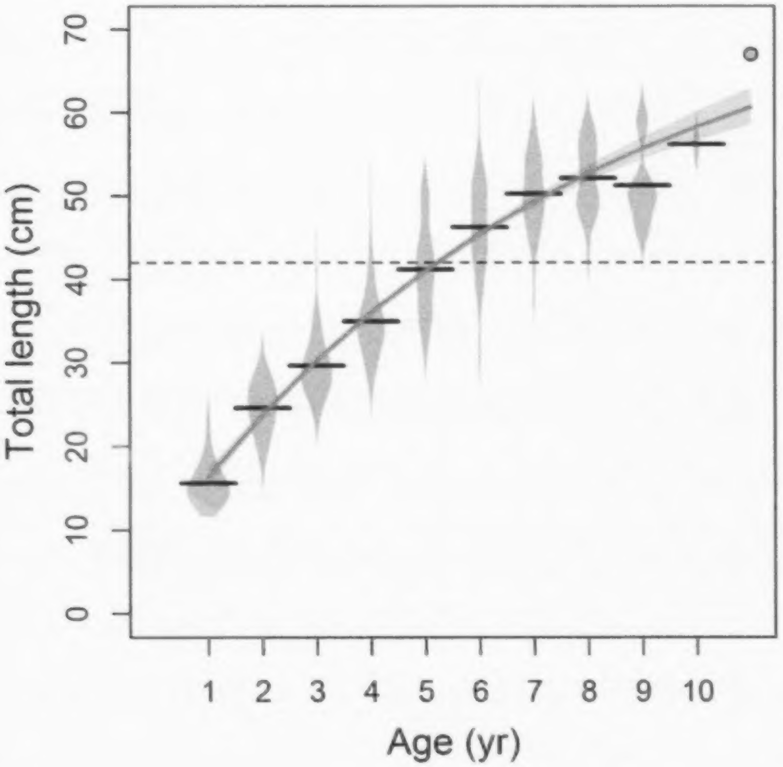
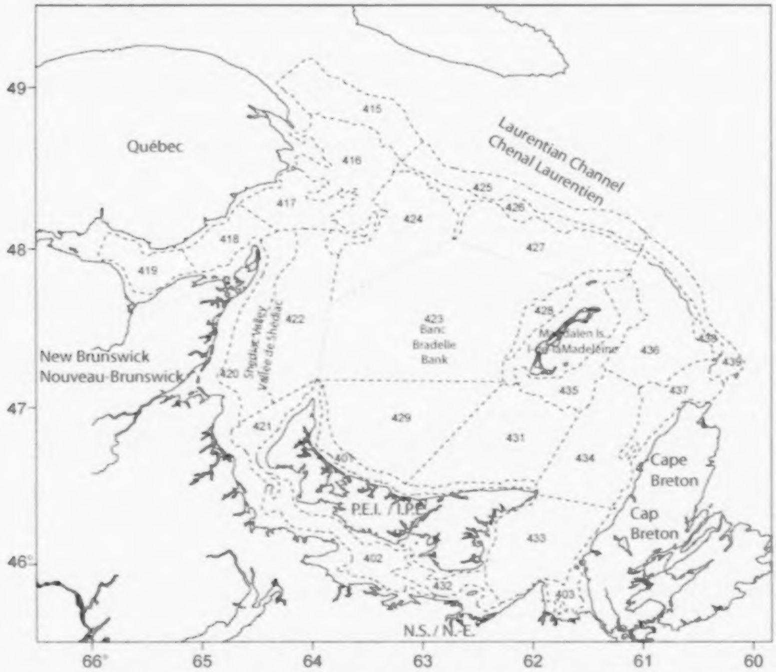


*Figure 1. Length at age of Winter Skate in the southern Gulf of St. Lawrence. Shading shows the distribution and black lines the mean length at age. The red line shows the predicted length at age based on a von Bertalanffy model (95% confidence bands given by the red shading). Dashed line shows the length at the start of the adult stage.*


49
48
47
46
66°
65
64
63
62
61
60
Québec
Laurentian Channel
Chenal Laurentien
New Brunswick
Nouveau-Brunswick
Shediac Valley
Vallée de Shediac
423
Banc
Bradelle
Bank
Magdalen Is.
Îles de la Madeleine
Cape Breton
Cap Breton
P.E.I. / Î.P.E.
N.S. / N.-É.
415
416
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436
437
438
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401
402
403

*Figure 2. Stratification scheme for the southern Gulf of St. Lawrence September trawl survey. Strata depths are as follows: < 50 fathoms: 401 to 403, 417 to 424, 427 to 436; 51 to 100 fathoms: 416, 426, 437 and 438; >100 fathoms: 415, 425, 439.*

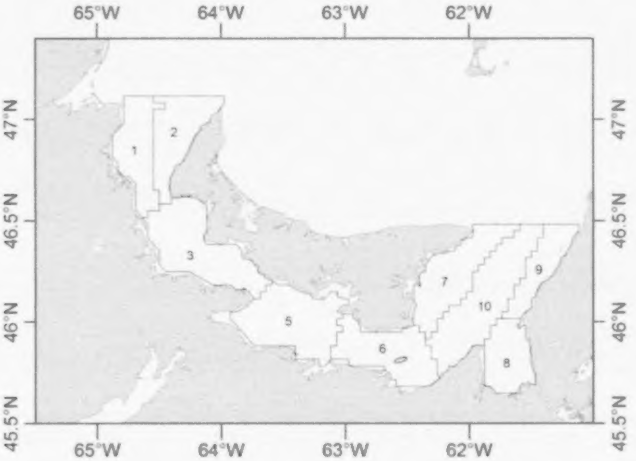
65°W
64°W
63°W
62°W
47°N
46.5°N
46°N
45.5°N
1
2
3
5
6
7
8
9
10

*Figure 3. Stratification scheme for the Northumberland Strait trawl survey.*

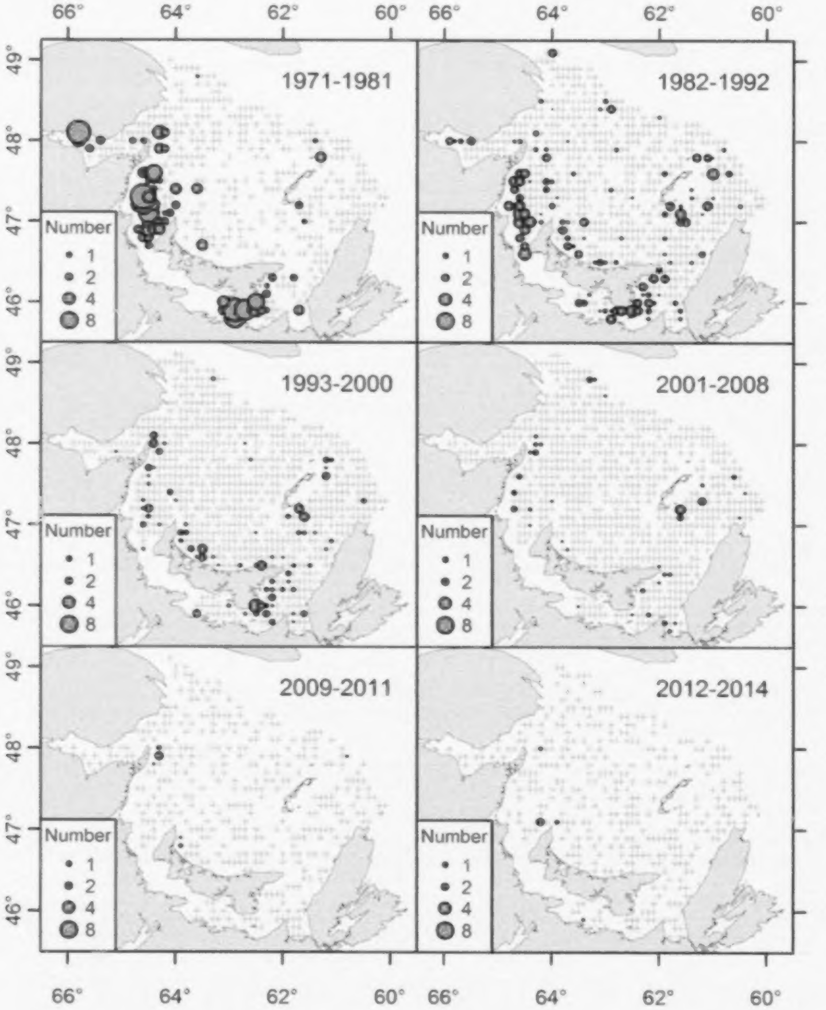
66°
64°
62°
60°
49°
48°
47°
46°
1971-1981
1982-1992
1993-2000
2001-2008
2009-2011
2012-2014
Number
1
2
4
8

*Figure 4. The geographic distribution of catches of adult Winter Skate (≥ 42 cm TL) in the September bottom-trawl survey of the southern Gulf of St. Lawrence by time period. Catches were aggregated on a 0.1°W x 0.1°N grid and averaged within time periods. Crosses indicate locations that were fished without catching Winter Skate. Circle area is proportional to catch rate.*

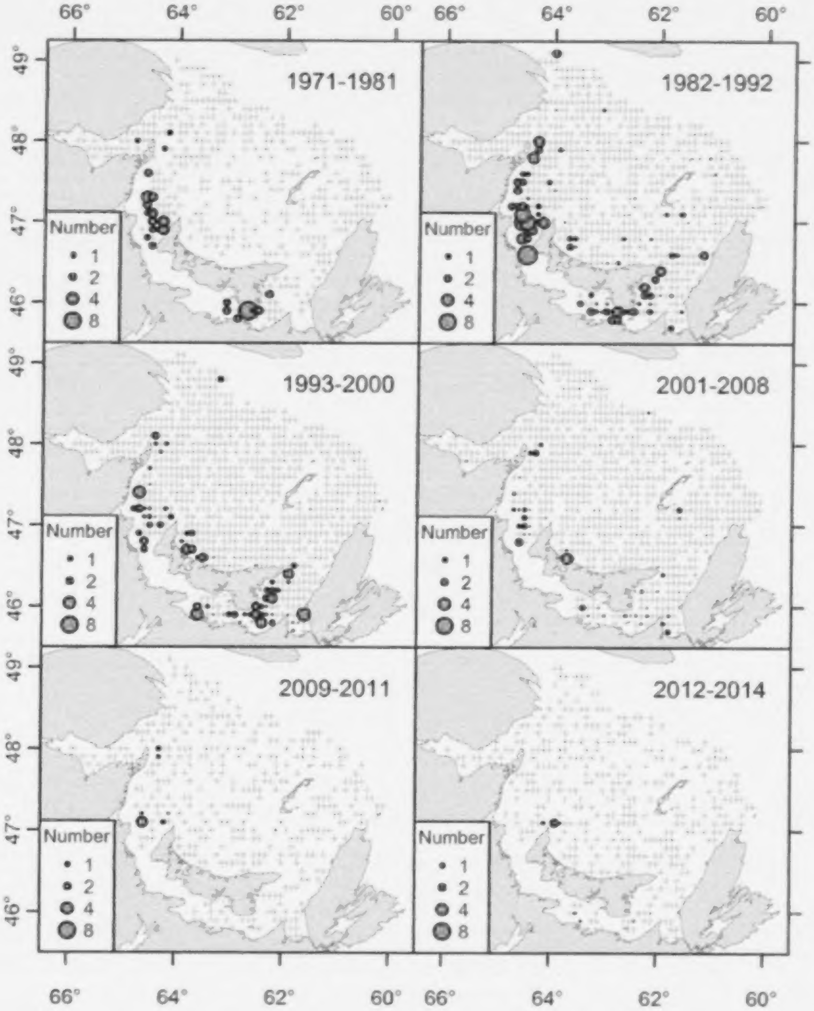
66°
64°
62°
60°
49°
48°
47°
46°
1971-1981
1982-1992
1993-2000
2001-2008
2009-2011
2012-2014
Number
1
2
4
8

*Figure 5. The geographic distribution of catches of juvenile Winter Skate (21 to 41 cm TL) in the September bottom-trawl survey of the southern Gulf of St. Lawrence by time period. Catches were aggregated on a 0.1°W x 0.1°N grid and averaged within time periods. Crosses indicate locations that were fished without catching Winter Skate. Circle area is proportional to catch rate.*

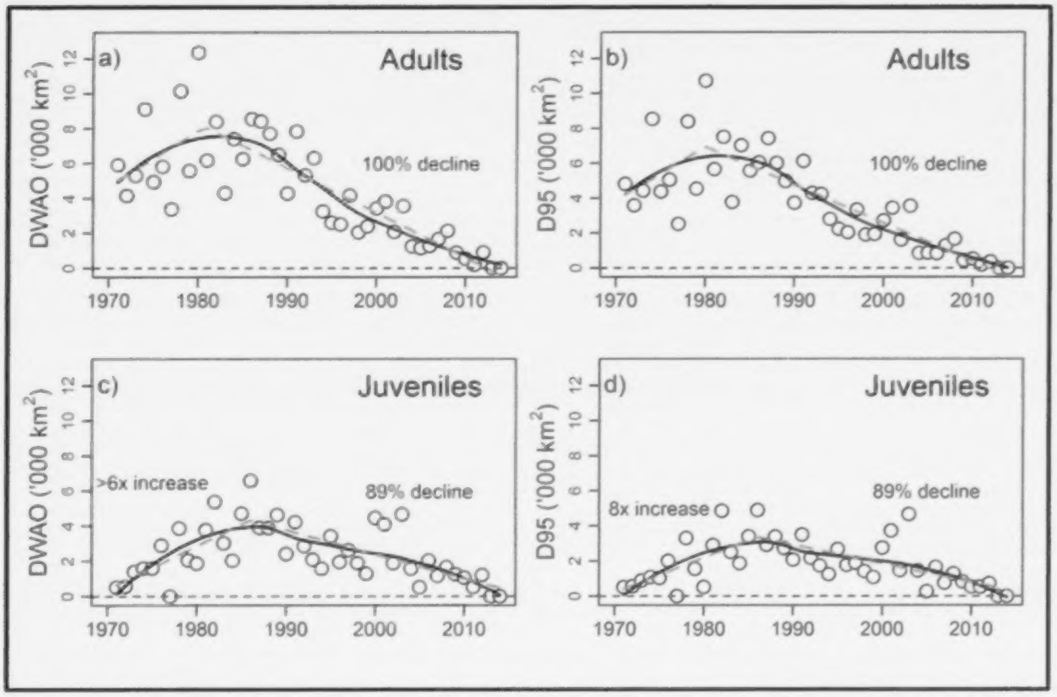

*Figure 6. Indices of geographic range for adult (≥42 cm TL; upper row panels a and b) and juvenile (21 to 41 cm TL; lower row panels c and d) Winter Skate in the sGSL. Design-Weighted Area Occupied (DWAO; left column panels a and c) is the area where catches exceeded 0, with the area associated with each tow based on the survey design. D95 (right column panels b and d) is the estimated minimum area containing 95% of the population. Circles show the annual estimates. Solid lines describe the temporal trend based on a locally-weighted smoother (loess). Dashed line show a segmented regression fit to the data with the inset text representing the changes in the values for each component of the segmented regression period.*

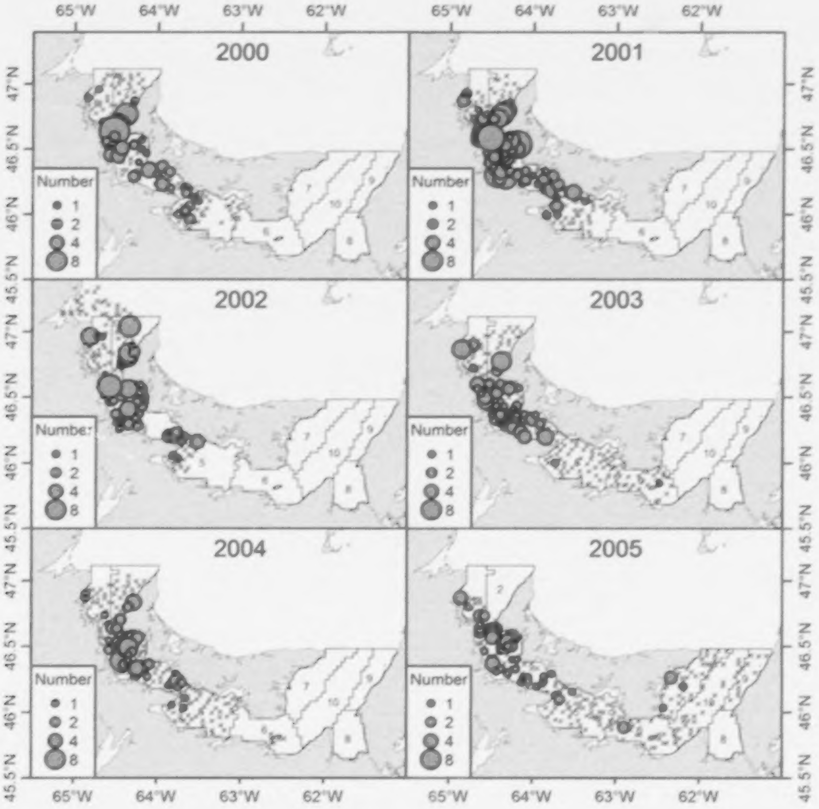
65°W
64°W
63°W
62°W
47°N
46.5°N
46°N
45.5°N
2000
2001
2002
2003
2004
2005
Number
1
2
4
8

*Figure 7. Catches (expressed as a catch rate, number of fish per tow) of Winter Skate (all sizes) in the July and August bottom-trawl survey of the Northumberland Strait, 2000 to 2005. Circle area is proportional to catch rate. Crosses indicate locations that were fished but no Winter Skate were caught.*

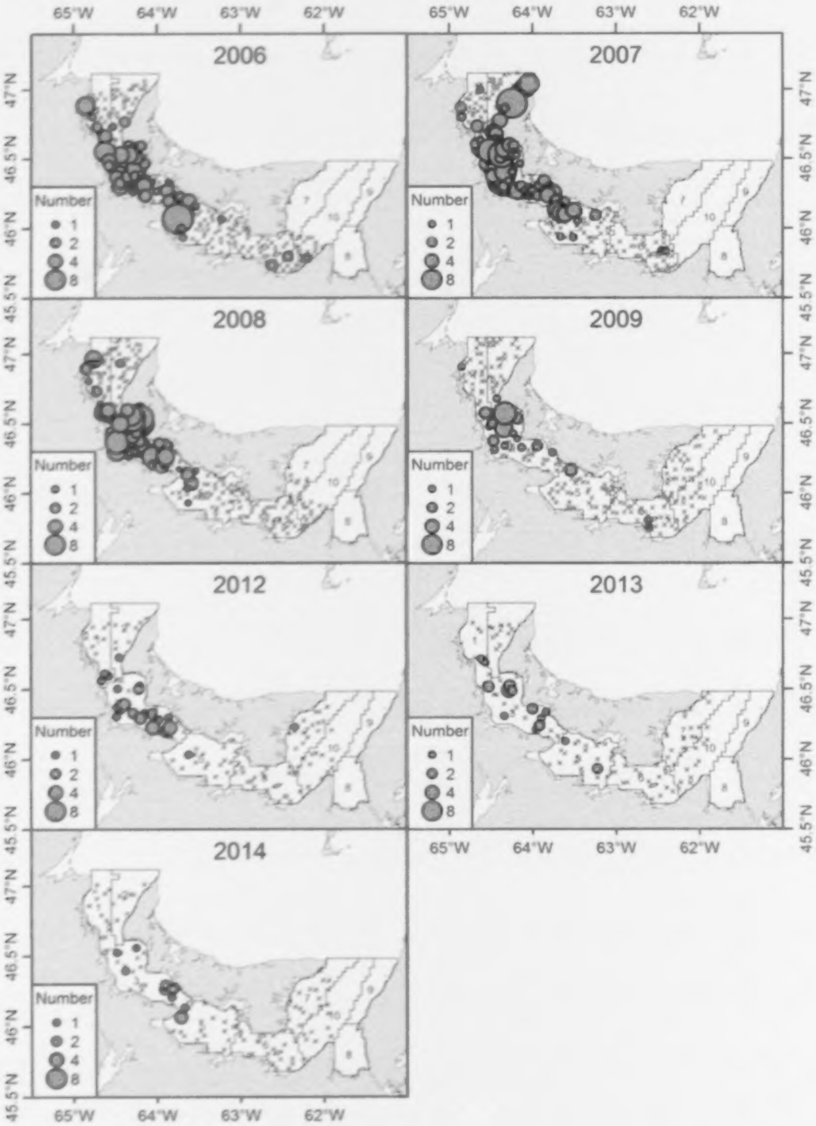
2006
2007
2008
2009
2012
2013
2014
Number
1
2
4
8
65°W
64°W
63°W
62°W
47°N
46.5°N
46°N
45.5°N

*Figure 7 (continued). Catches (expressed as a catch rate, number of fish per tow) of Winter Skate (all sizes) in the July and August bottom-trawl survey of the Northumberland Strait, 2006 to 2009 and 2012 to 2014. Circle area is proportional to catch rate. Crosses indicate locations that were fished but no Winter Skate were caught.*

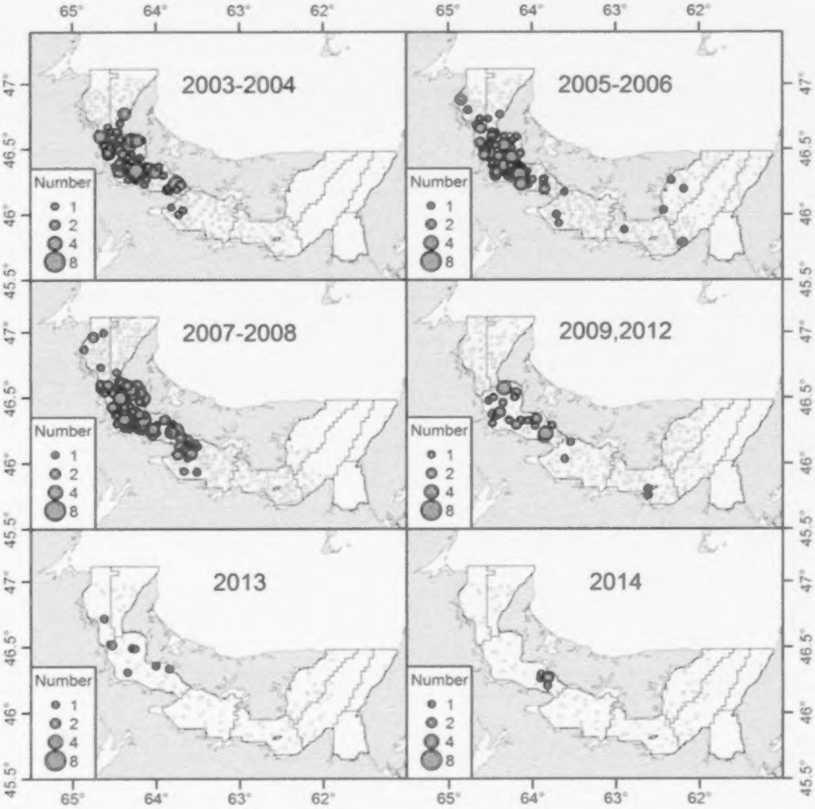
65°
64°
63°
62°
47°
46.5°
46°
45.5°
2003-2004
2005-2006
2007-2008
2009,2012
2013
2014
Number
1
2
4
8

*Figure 8. Catches (expressed as a catch rate, number of fish per tow) of adult Winter Skate (≥42 cm TL) in the July and August bottom-trawl survey of the Northumberland Strait, 2003 to 2014, excluding 2010 and 2011. Circle area is proportional to catch rate. Crosses indicate locations that were fished but no adult Winter Skate were caught.*

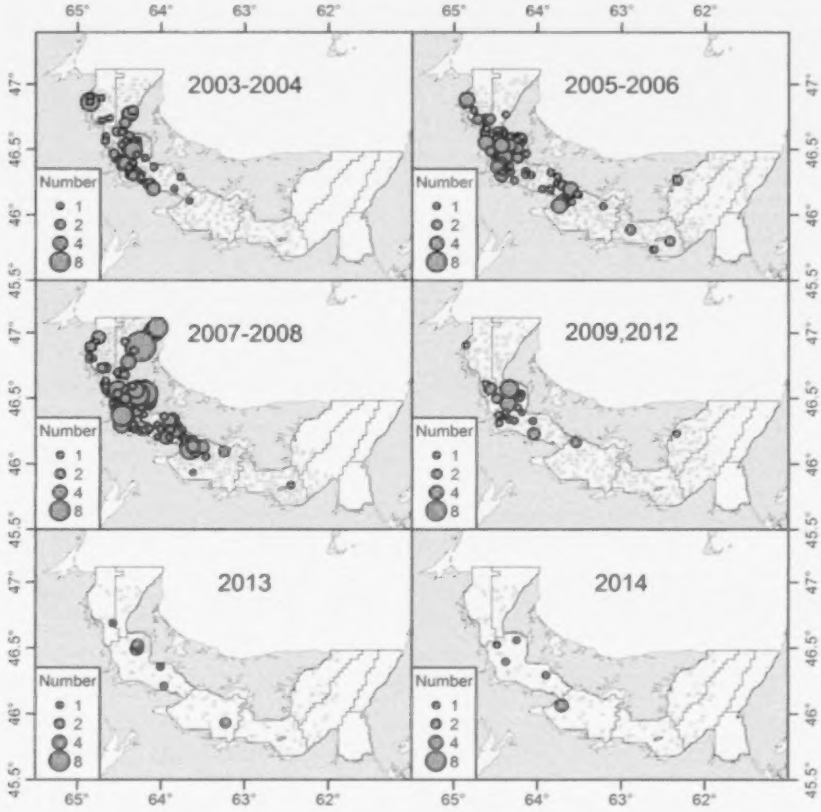
2003-2004
2005-2006
2007-2008
2009,2012
2013
2014
Number
1
2
4
8
65°
64°
63°
62°
47°
46.5°
46°
45.5°

*Figure 9. Catches (expressed as a catch rate, number of fish per tow) of juvenile Winter Skate (21 to 41 cm TL) in the July-August bottom-trawl survey of the Northumberland Strait, 2003 to 2014, excluding 2010 and 2011. Circle area is proportional to catch rate. Crosses indicate locations that were fished but no juvenile Winter Skate were caught.*

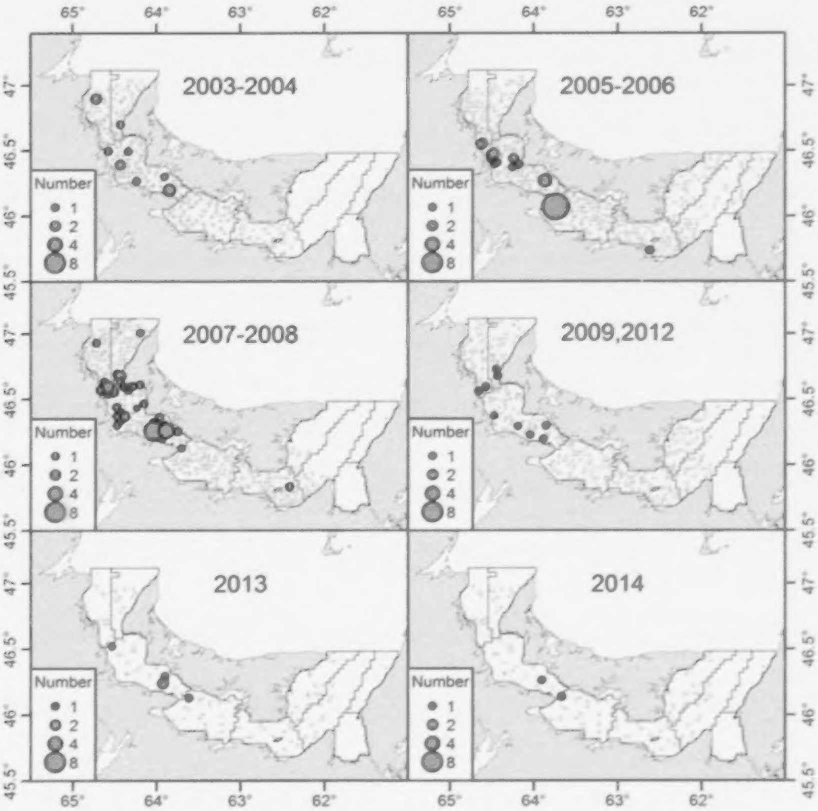
2003-2004
2005-2006
2007-2008
2009,2012
2013
2014
Number
1
2
4
8
65°
64°
63°
62°
47°
46.5°
46°
45.5°

*Figure 10. Catches (expressed as a catch rate, number of fish per tow) of Winter Skate recruits (<21 cm TL) in the July-August bottom-trawl survey of the Northumberland Strait, 2003 to 2014, excluding 2010 and 2011. Circle area is proportional to catch rate. Crosses indicate locations that were fished but no Winter Skate of recruit size were caught.*

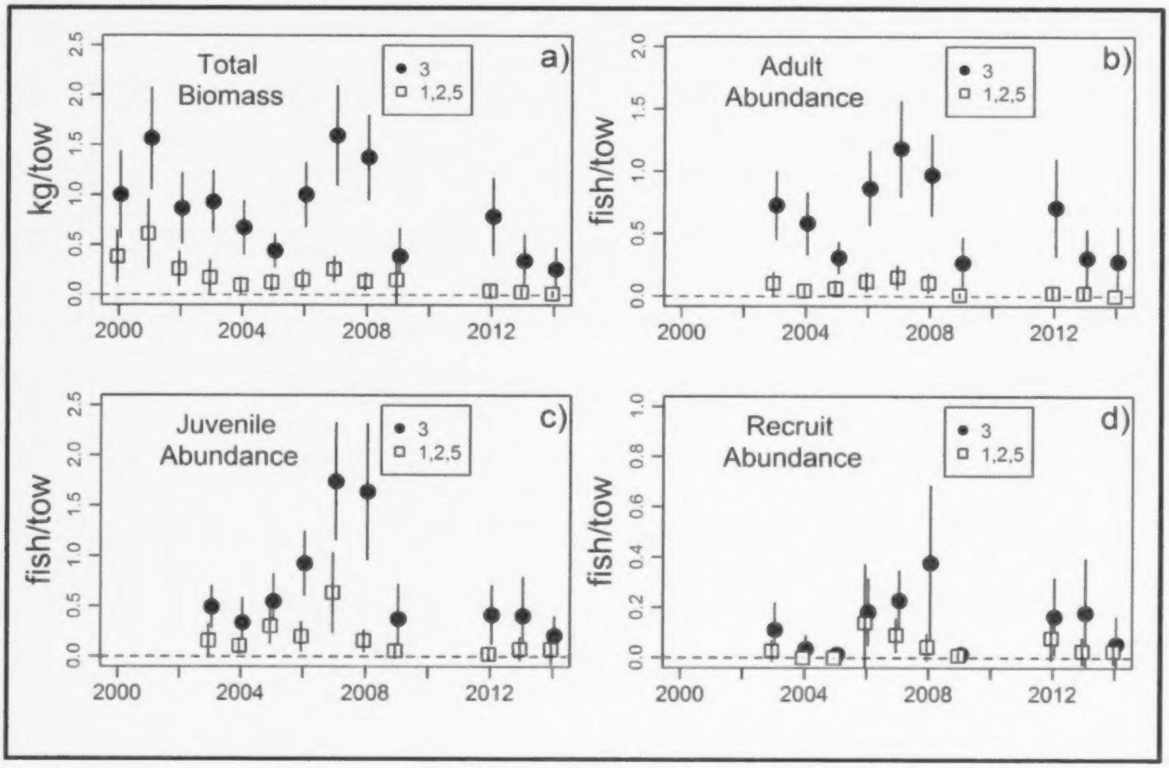

*Figure 11. Catch rates of Winter Skate in stratum 3 (closed circles) and in strata 1,2 and 5 combined (open squares) of the Northumberland Strait survey in terms of total biomass (kg per tow, panel a) and in terms of abundance (fish per tow) for adult (panel b), juvenile (panel c) and recruit sizes (panel d). In each panel, the symbol is the mean and the vertical lines represent ±2SE.*

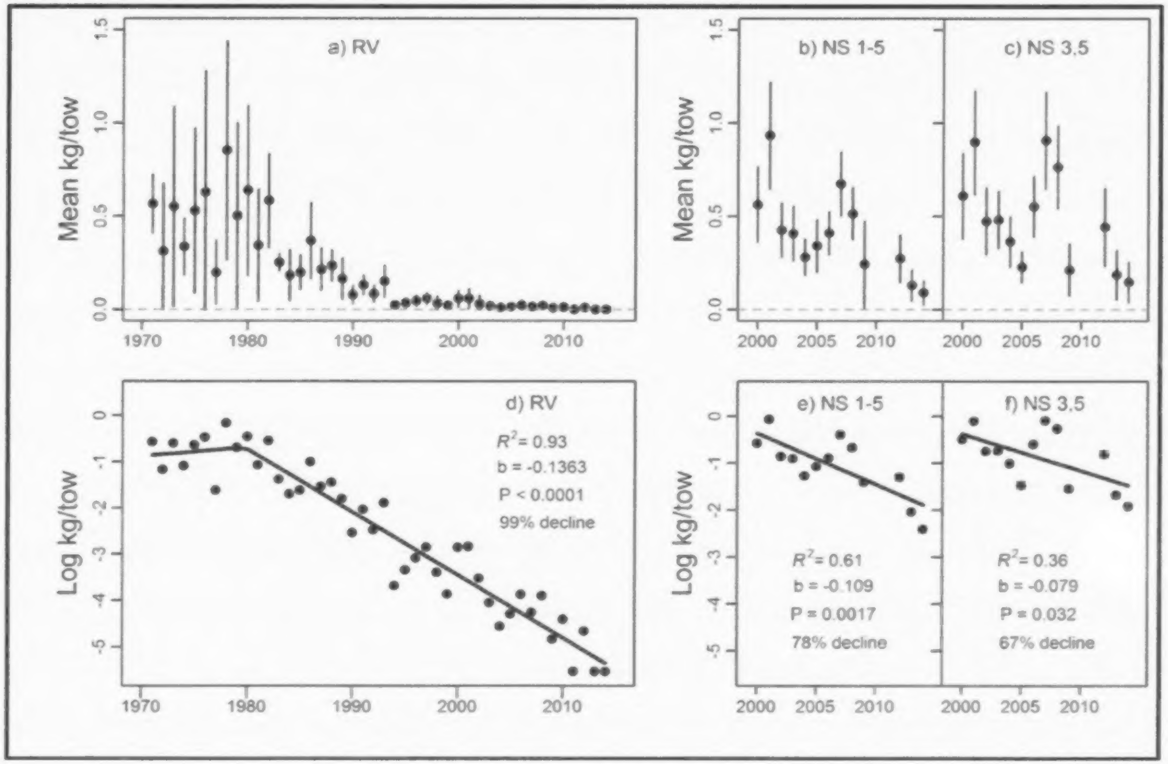

*Figure 12. Biomass indices for Winter Skate (all lengths) in the September RV survey (panels a and d; RV) and the Northumberland Strait survey (panels b, c, e, f; NS). The symbols are the mean and the vertical lines represent ±2SE. The 24 strata fished since 1971 (415-439) are used for the RV survey (panels a and d) and strata 1-5 (the strata fished since 2000; panels b and e) or 3 and 5 (the region not covered by the standard RV strata; panels c and f) are shown for the NS survey. The exponential declines in biomass are estimated in panels d to f based on the regression of the log of the biomass indices versus year. A segmented regression is used in panel d and three outliers (0.0003 in 2011 and 0 in 2013 and 2014) were replaced by one-half the second lowest non-zero value observed (0.0079 in 2009) before logging the data. The estimated breakpoint was in 1980. In panels d to f, $R^2$ is the proportion of variation in log catch rates explained by the regression model, P is the significance level of the model, and b is the estimated slope (since 1980 in panel d). The percent decline is calculated over the time period covered by the regression, since 1980 in panel d.*

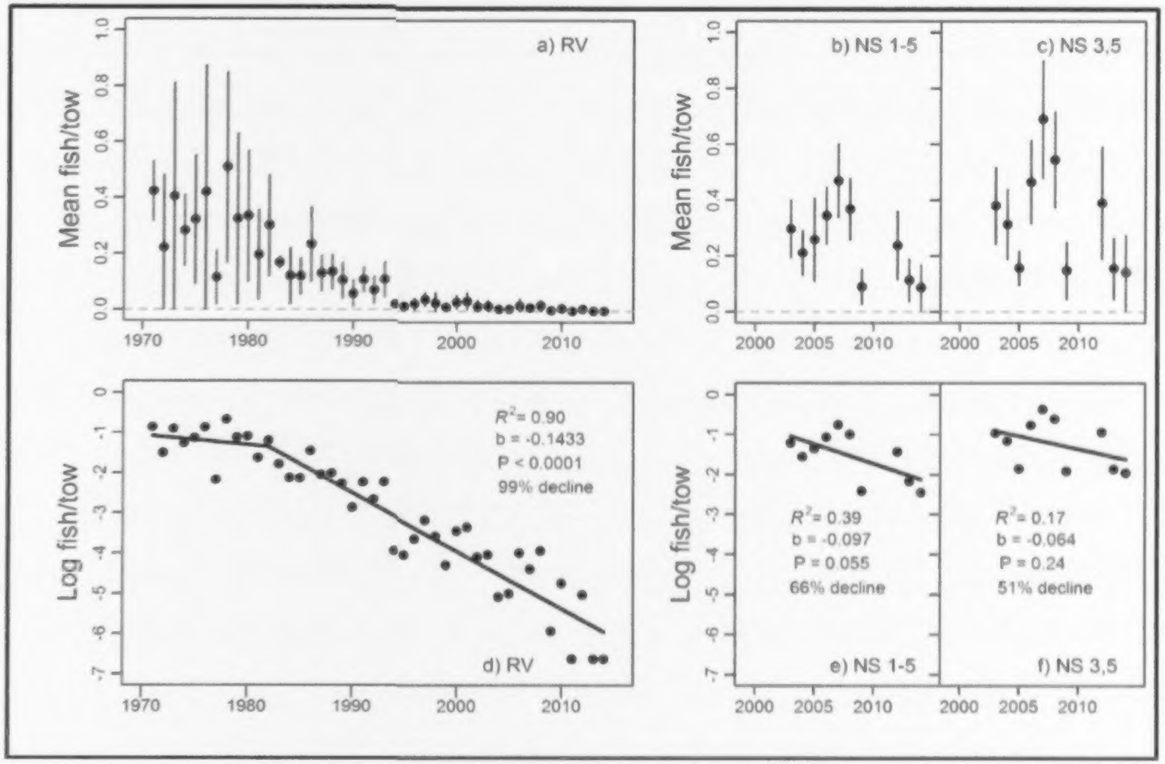

*Figure 13. Abundance indices for adult Winter Skate (≥ 42 cm) in the September RV survey (panels a and d; RV) and the Northumberland Strait survey (panels b, c, e, f; NS). The symbols are the mean and the vertical lines represent ±2SE. The 24 strata fished since 1971 (415-439) are used for the RV survey (panels a and d) and strata 1-5 (the strata fished since 2000; panels b and e) or 3 and 5 (the region not covered by the standard RV strata; panels c and f) are shown for the NS survey. The exponential declines in abundance are estimated in panels d to f based on the regression of log abundance versus year. A segmented regression is used in panel d and three outliers (0.0003 in 2011 and 0 in 2013 and 2014) were replaced by one-half the second lowest non-zero value observed (0.0027 in 2009) before logging the data. The estimated breakpoint was in 1982. In panels d to f, $R^2$ is the proportion of variation in log catch rates explained by the regression model, P is the significance level of the model, and b is the estimated slope (since 1982 in panel d). The percent decline is calculated over the time period covered by the regression, since 1982 in panel d.*

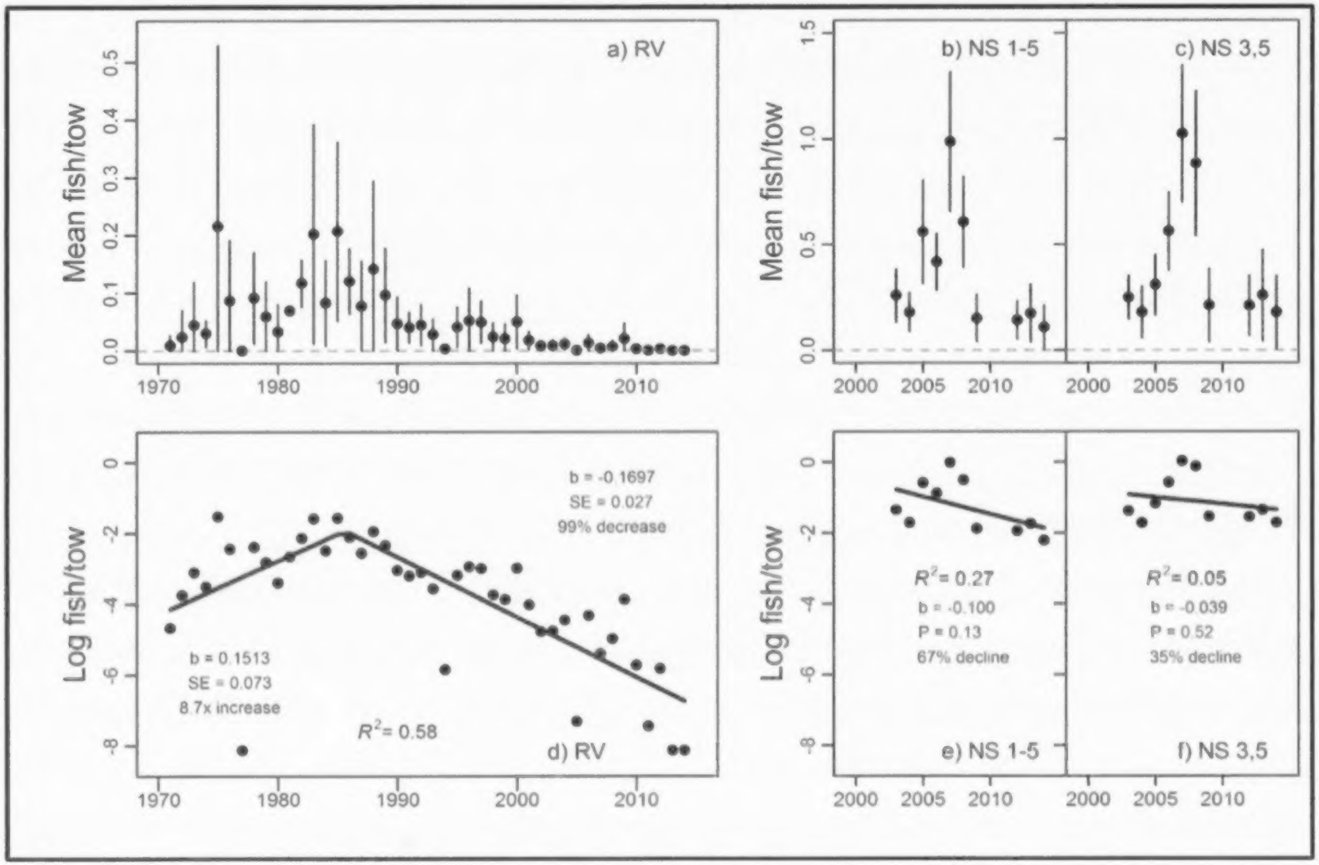

*Figure 14. Abundance indices for juvenile Winter Skate (21 to 41 cm) in the September RV survey (panels a and d; RV) and the Northumberland Strait survey (panels b, c, e, f; NS). The symbols are the mean and the vertical lines represent ±2SE. The 24 strata fished since 1971 (415-439) are used for the RV survey (panels a and d) and strata 1-5 (the strata fished since 2000; panels b and e) or 3 and 5 (the region not covered by the standard RV strata; panels c and f) are shown for the NS survey. The exponential declines in abundance are estimated in panels d to f based on the regression of log abundance versus year. A segmented regression is used in panel d and three outliers (0 in1977, 2013, 2014) were replaced by one-half the lowest non-zero value observed (0.00059 in 2011) before logging the data. The estimated breakpoint was in 1986. In panels d to f, $R^2$ is the proportion of variation in log catch rates explained by the regression model, P is the significance level of the model, and b and SE are the estimated slope and its standard error (for the nearest segment in panel d).*

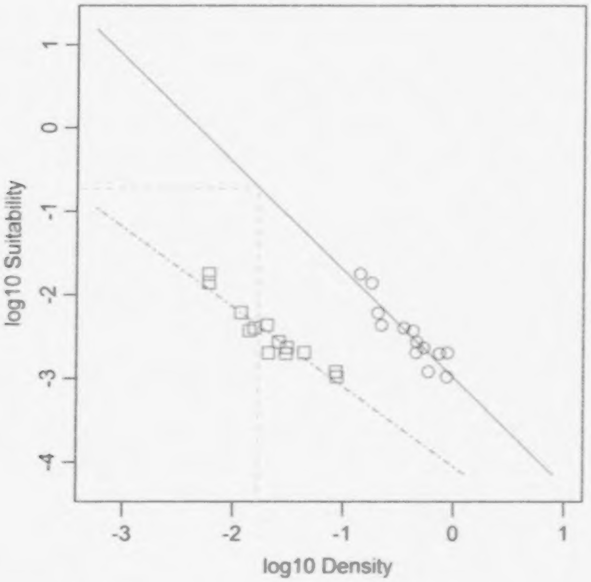

*Figure 15. Distribution of the sGSL Winter Skate population between the central Northumberland Strait (strata 3 and 5 of the NS survey, green circle and solid line) and areas outside of this region (RV survey strata 415 to 39, red squares and dashed line), assuming that distribution follows the Ideal Free Distribution. When density within NS strata 3 and 5 is below 0.017 kg per ha (log10 density = -1.775), all Winter Skate are expected to be found in these two strata. Density is in units of kg per ha.*

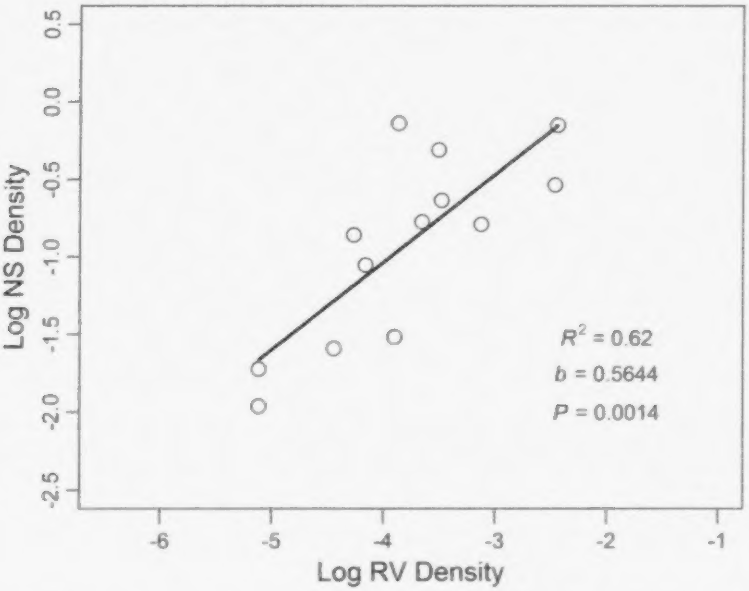

*Figure 16. Relationship between $\log_e$ Winter Skate density (kg per ha) in the NS (strata 3 and 5) and RV (strata 415 to 439) surveys during 2000 to 2009 and 2012 to 2014. $R^2$ is the squared correlation coefficient, b is the regression slope and P its significance level. RV catch rates have been adjusted to be equivalent to those in the NS survey.*

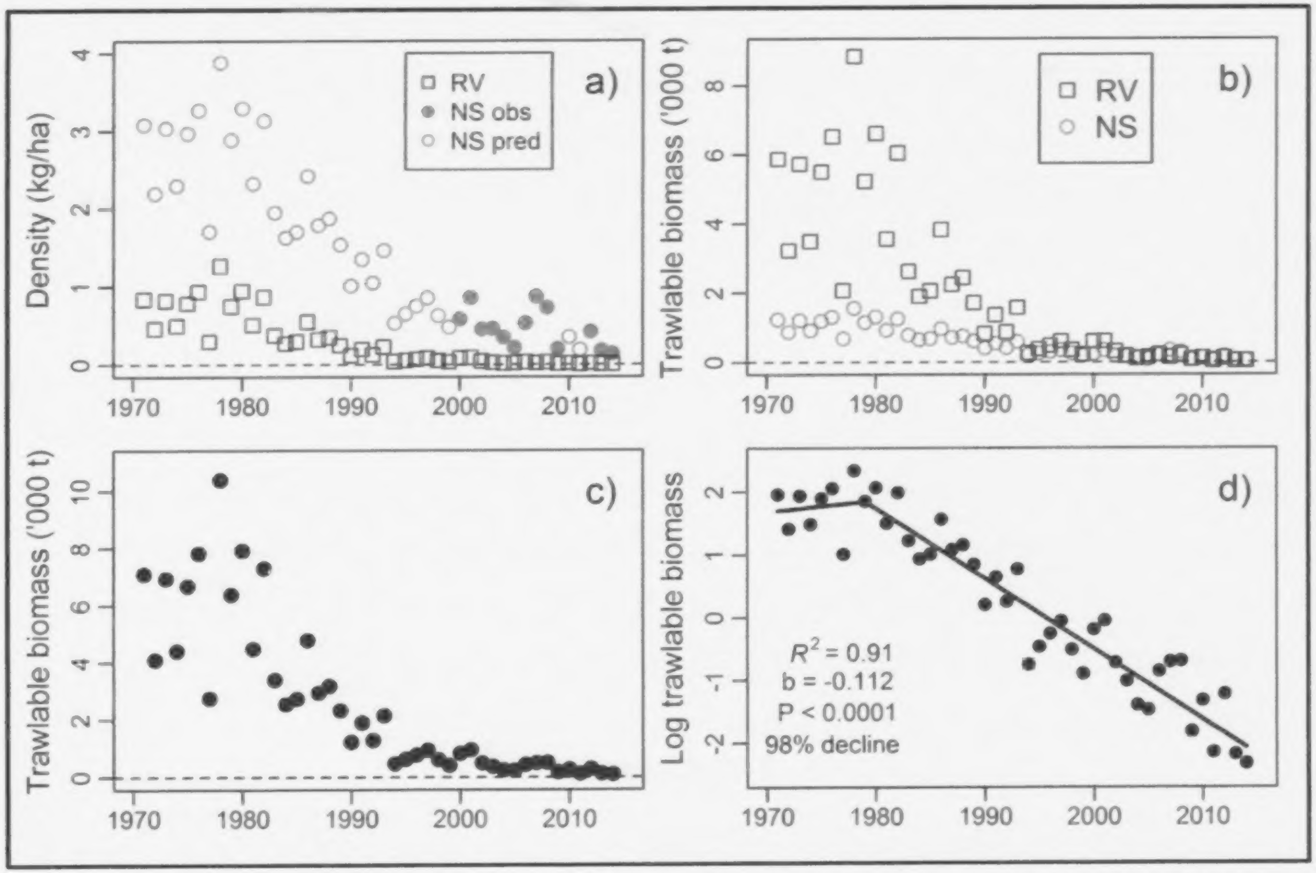

*Figure 17. Estimated decline in total trawlable biomass of sGSL Winter Skate based on indices that incorporate the predicted biomass in the unsampled regions of the Northumberland Strait. The estimated density (kg per ha; panel a) and trawlable biomass (1000 t; panel b) are shown by open blue squares for the RV survey (strata 415-439) and closed red circles for the NS survey (strata 3 and 5). The open red circles in panels a and b show predicted density and trawlable biomass for the area covered by the NS survey. Closed black circles in panels c and d show combined trawlable biomass estimates for the RV and NS surveys with RV catch rates adjusted to be equivalent to those in the NS survey. The line in panel d shows the fit of the segmented regression of the natural log of total trawlable biomass against year. $R^2$ is the proportion of the variation in log biomass accounted for by the regression, P is its significance level, and b is the slope after the estimated break-point in 1979. The estimated decline since 1979 is 98%.*

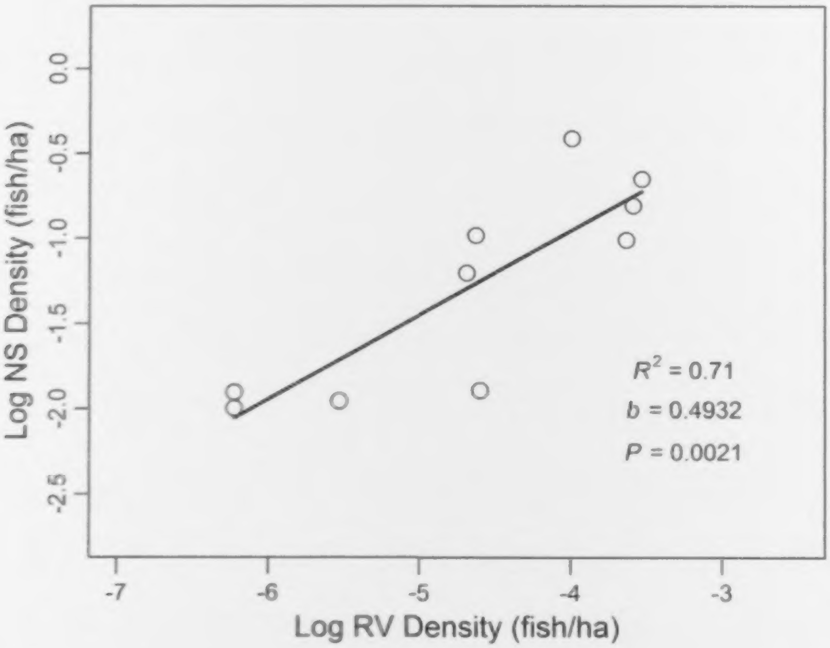

*Figure 18. Relationship between densities (fish per ha; on the natural log scale) of adult Winter Skate in the NS (strata 3 and 5) and RV (strata 415-439) surveys in 2000 to 2009 and 2012 to 2014. RV catch rates have been adjusted to be equivalent to those in the NS survey. $R^2$ is the squared correlation coefficient, b is the regression slope and P its significance level.*

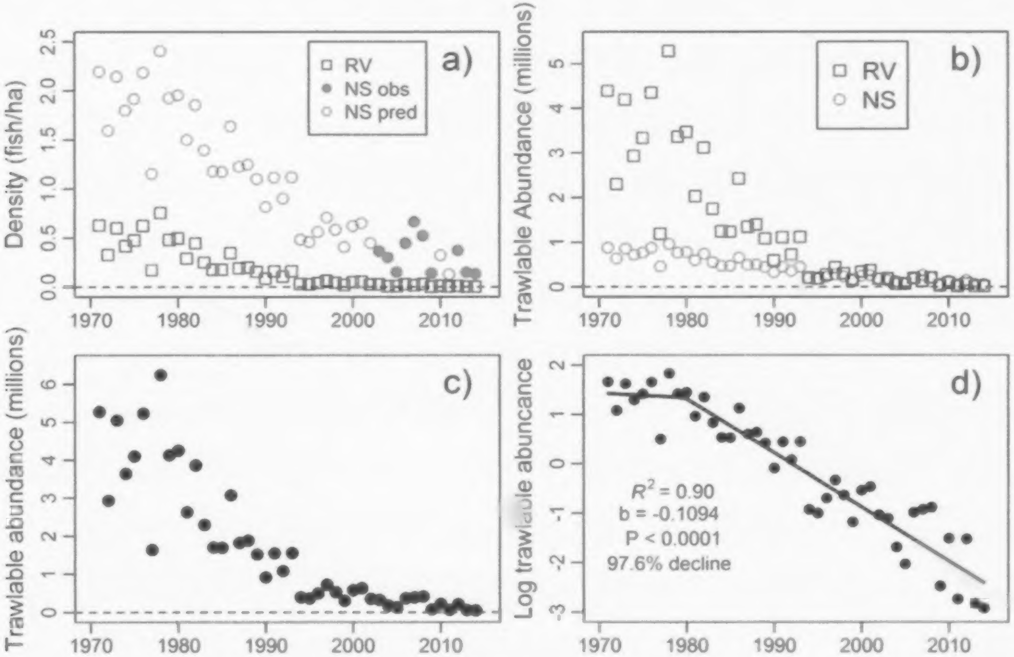

*Figure 19. Estimated decline in adult abundance of sGSL Winter Skate incorporating predicted abundance in unsampled regions of the Northumberland Strait. The estimated density (fish per ha; panel a) and trawlable abundance (millions; panel b) are shown by open blue squares for the RV survey (strata 415 to 439) and closed red circles for the NS survey (strata 3 and 5). The open red circles in panels a and b show predicted density and trawlable abundance for the NS survey. Closed black circles in panels c and d show combined abundance for the RV and NS surveys. RV catch rates have been adjusted to be equivalent to those in the NS survey. The line in panel d shows the fit of the segmented regression of $\log_e$ total trawlable biomass against year. $R^2$ is the proportion of the variation in $\log_e$ biomass accounted for by the regression, P is its significance level, and b is the slope after the estimated break-point in 1980. The estimated decline since 1980 is 97.6%.*

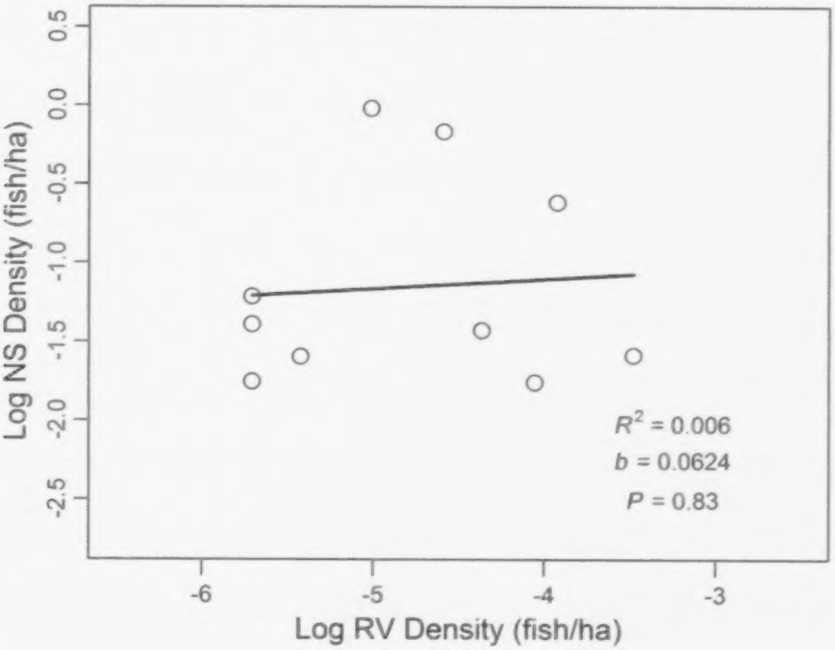

*Figure 20. Relationship between densities (fish per ha on the natural log scale) of juvenile Winter Skate in the NS (strata 3 and 5) and RV (strata 415 to 439) surveys in 2000 to 2009 and 2012 to 2014. RV catch rates have been adjusted to be equivalent to those in the NS survey. $R^2$ is the squared correlation coefficient, b is the regression slope and P its significance level.*

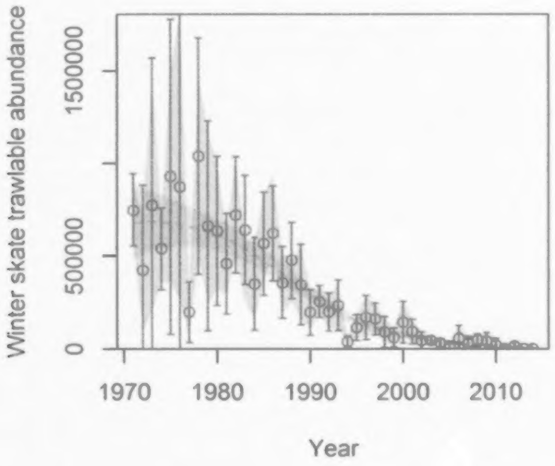

*Figure 21. Estimated trawlable abundance of Winter Skate based on the RV survey. Points and vertical error bars are the stratified mean estimate and analytical 95% confidence intervals, the grey shaded area is the 95% confidence interval based on bootstrapping of RV survey sets and the red dashed line and red shaded area are the mean and 95% confidence intervals of the bootstrapped and smoothed estimates of trawlable abundance.*

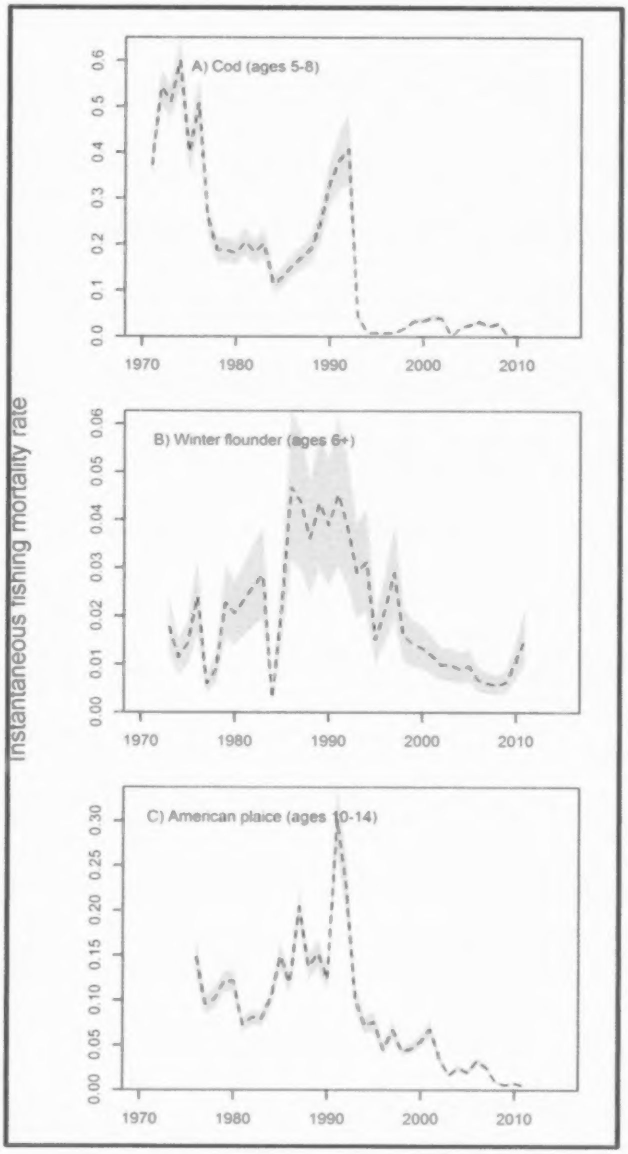

*Figure 22. Estimated instantaneous fishing mortality rate (maximum likelihood estimate, dashed line, and 95% credibility interval, grey area) of the key commercially fished species for which the directed fisheries are important sources of Winter Skate discards. Values are taken from the most recent assessments for Winter Flounder (Morin et al. 2012) and American Plaice (Morin et al. 2013), and recent population modelling for Atlantic Cod (Swain and Benoît 2015).*

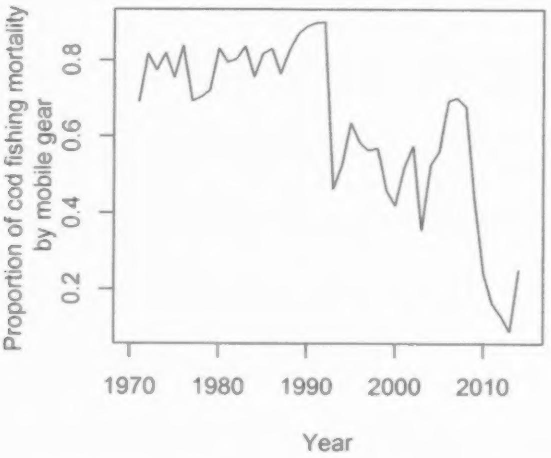

*Figure 23. Annual proportion of the total fishing mortality of cod that resulted from catches in the mobile gear component of the fishery.*

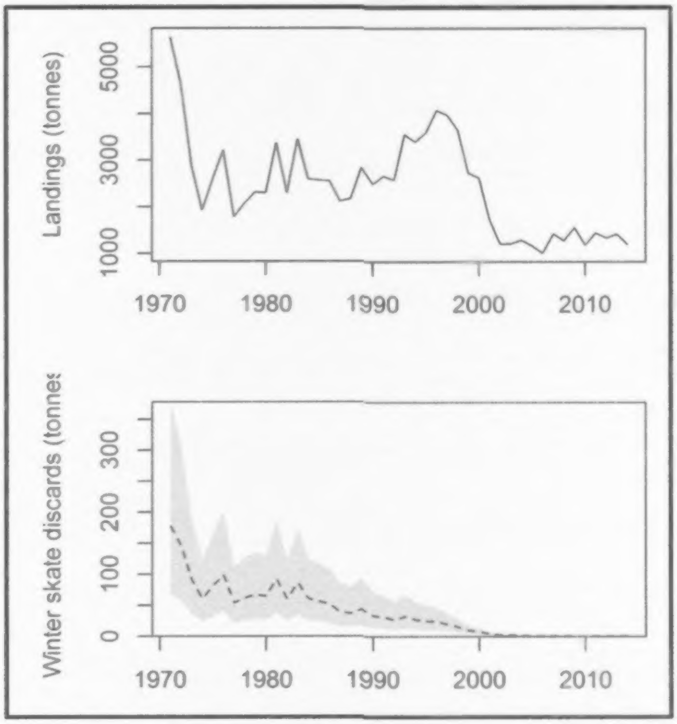

*Figure 24. Reported landings of scallops (top panel) and estimated discards of Winter Skate (bottom panel; mean and 95% confidence interval) in the sGSL scallop fishery.*

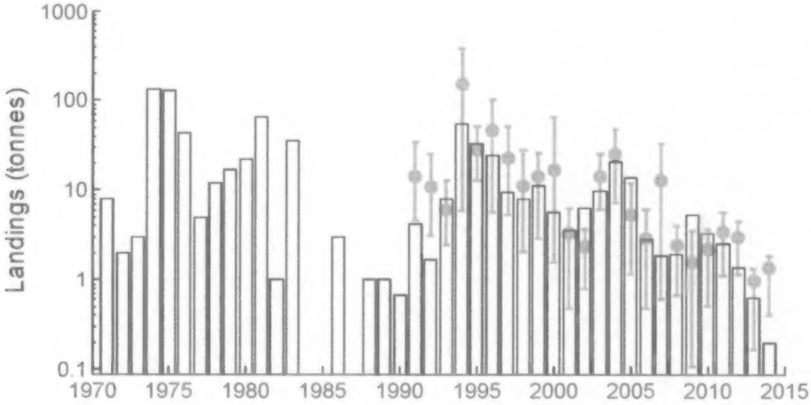

*Figure 25. Reported landings of skates (not specified) in the sGSL, 1971 to 2014 (bars) and estimated landings based on fisheries observer reports of retained skate catches, 1991 to 2014 (mean and 95% confidence interval; grey symbol and error bars). Note the log-scale for landings (tonnes).*

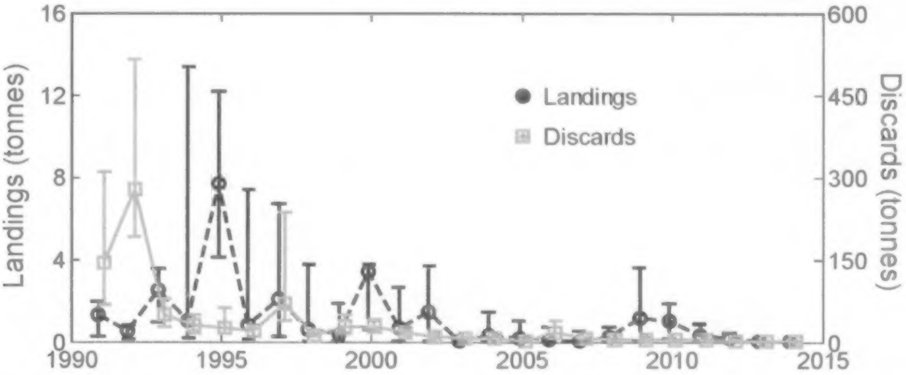

*Figure 26. Estimated landings (tonnes; black circles) and discards (tonnes; grey squares) of sGSL Winter Skate based on at-sea observer records for the commercial groundfish and shrimp fisheries, 1991 to 2014. The error bars are estimated 95% confidence intervals. The annual values have been slightly horizontally offset to make the differences between the two series clearer. Note the use of separate y-axes for landings and discards.*

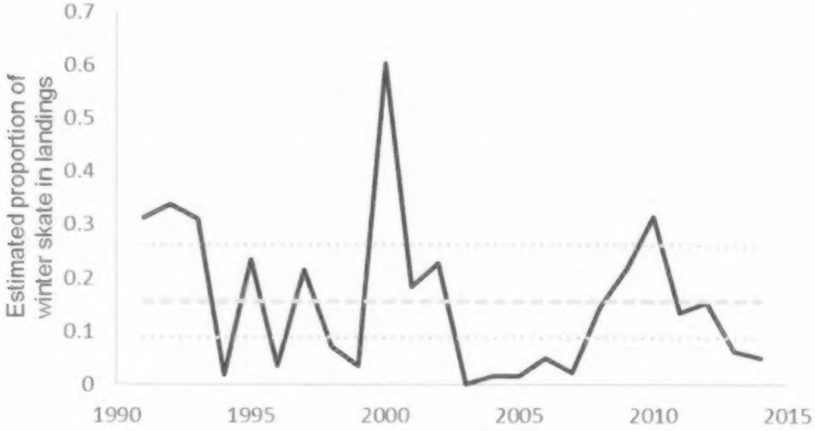

*Figure 27. Estimated annual proportion of Winter Skate in sGSL skate landings (black solid line) and mean proportion (0.157; solid grey line) and 95% confidence intervals (dash grey lines) for 1991 to 2014.*

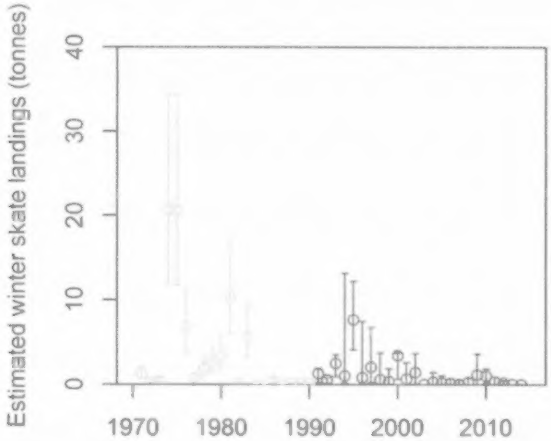

*Figure 28. Estimated Winter Skate landings (circle with 95% confidence interval error bars) in the sGSL based on reported skate landings and either annual at-sea observer reports (blue symbols and error bars) or a fixed proportion of Winter Skate in skate catches based on the 1991 to 2014 average (grey symbols and error bars).*

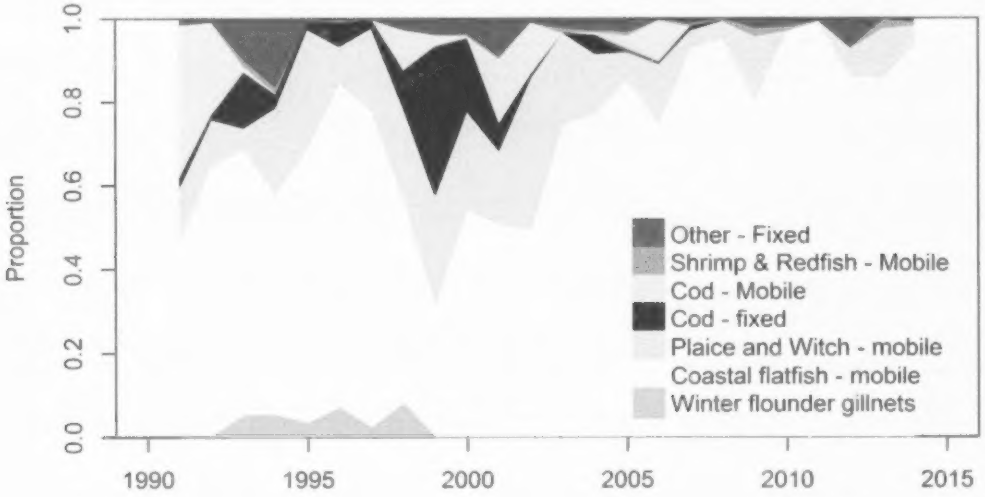

*Figure 29. Annual estimates of the contribution (proportion) of the various commercial fisheries to the discards of sGSL Winter Skate. Coastal flatfish mobile-gear fisheries are those that target Winter Flounder and Yellowtail Flounder.*

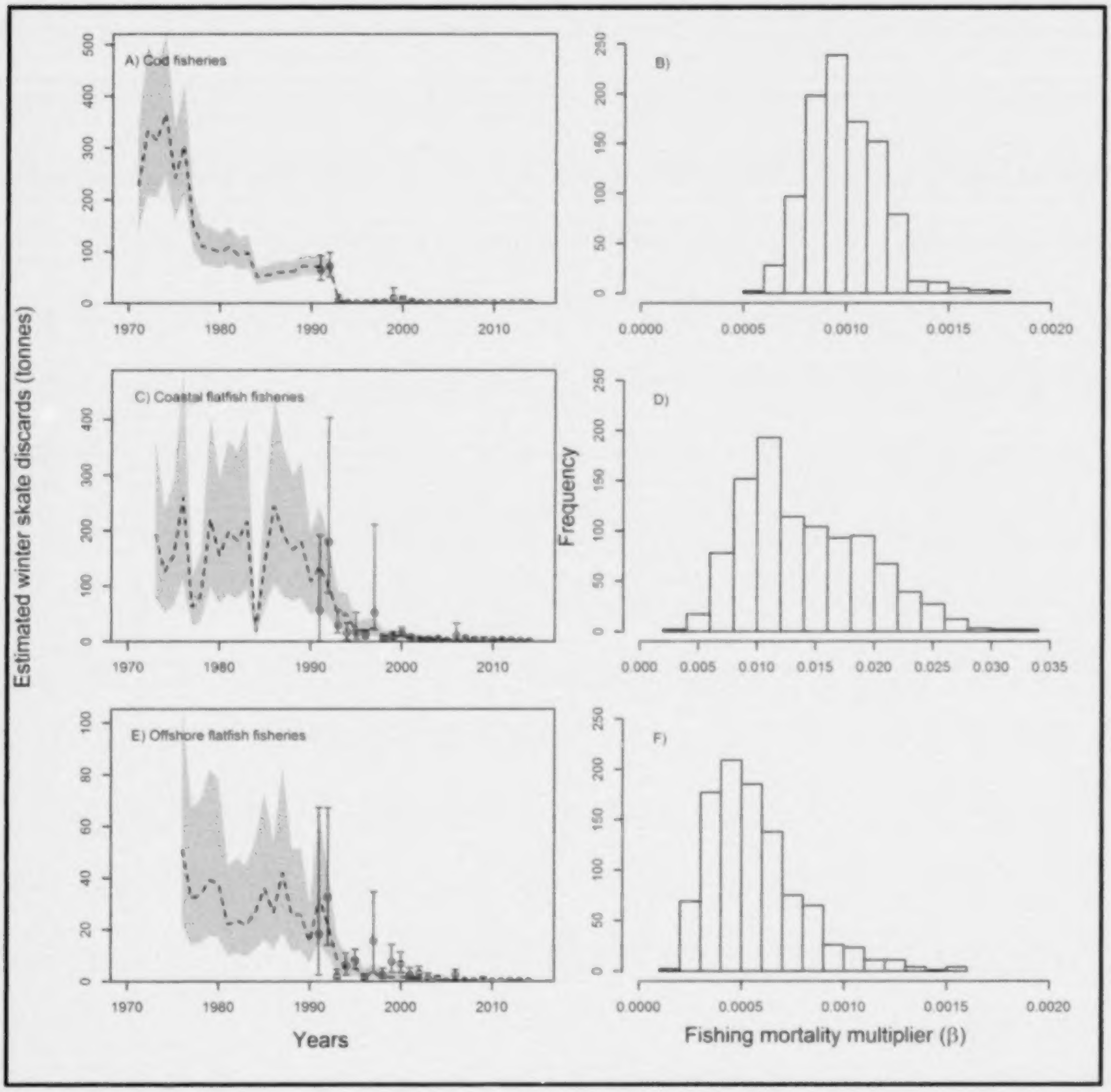

*Figure 30. Estimated Winter Skate discards (left column) and histogram of the bootstrapped values of the fishing mortality proportionality coefficient β ($b_S$, eq. 13) (right column) for each of the three major fisheries that incidentally capture Winter Skate (rows). Estimated discards and 95% confidence intervals are based on annual observations by fisheries observers (blue circles and bars) or derived using equation 13 based on the fishing mortality of the species targeted in each fishery (dashed line and grey shaded area).*

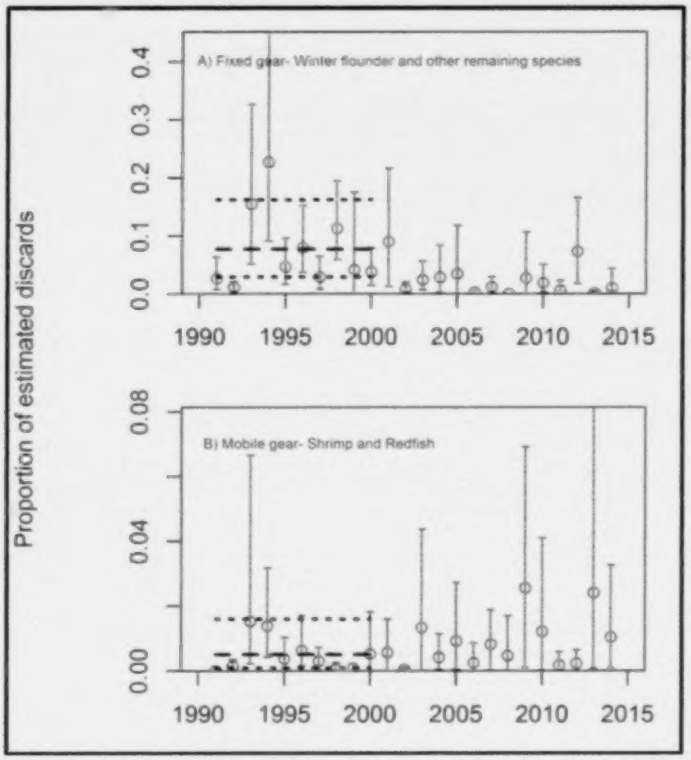

*Figure 31. Estimated proportion of Winter Skate discards originating from fisheries other than the main fisheries in Figure 29, specifically the fixed gear fisheries for Winter Flounder and other species, and the mobile gear fisheries targeted at shrimp and Redfish. The circles and error bars are annual means and 95% confidence intervals based on fisheries observer reports, and the long dashed line and dotted lines are respectively the means and 95% confidence intervals of the proportions for 1991 to 2000. In panel a) the mean proportion is 0.077 (95% CI: 0.029 to 0.162) and in panel b) the mean proportion is 0.005 (95% CI: 0.001 to 0.016).*

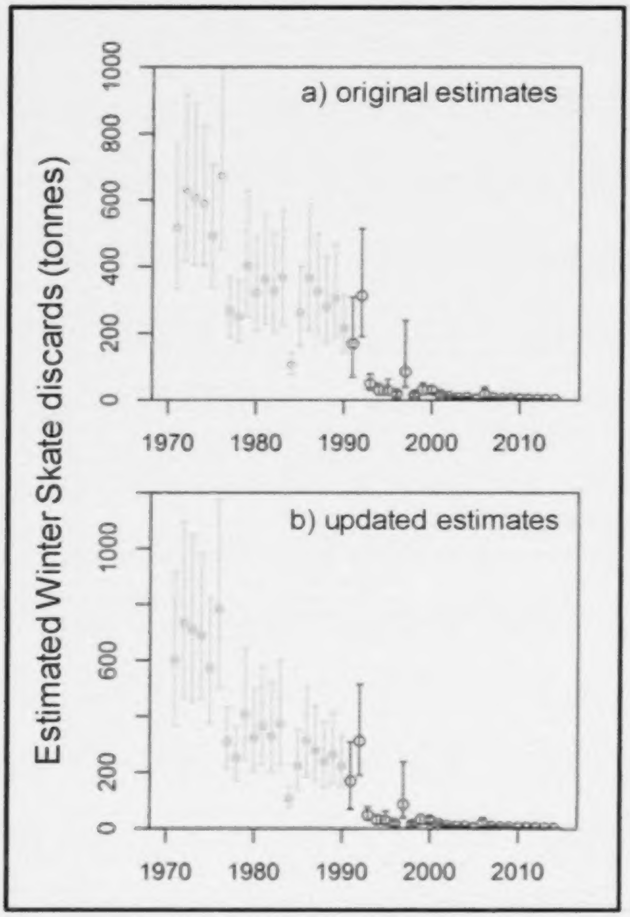

*Figure 32. Estimated total discards of Winter Skate (mean and 95% confidence intervals) in commercial and sentinel fisheries. The estimates for 1991 to 2014 (blue symbols and error bars) are annual estimates based on fisheries observer reports, while the estimates for 1971 to 1990 (grey symbols and error bars) are derived using eq. 13 for the three main fisheries capturing Winter Skate, adjusted for catches in other fisheries. Panel a shows the original estimates derived from preliminary assumptions for Winter Skate natural mortality, whereas panel b shows the updated estimates using natural mortality values estimated as part of preliminary population modelling.*

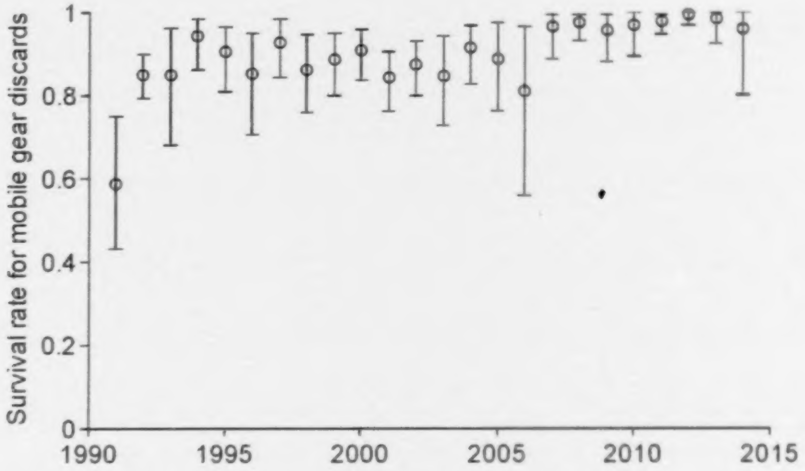

*Figure 33. Annual estimates (mean and 95% confidence interval) of the survival rate of Winter Skate discarded in mobile-gear fisheries, 1991 to 2014.*

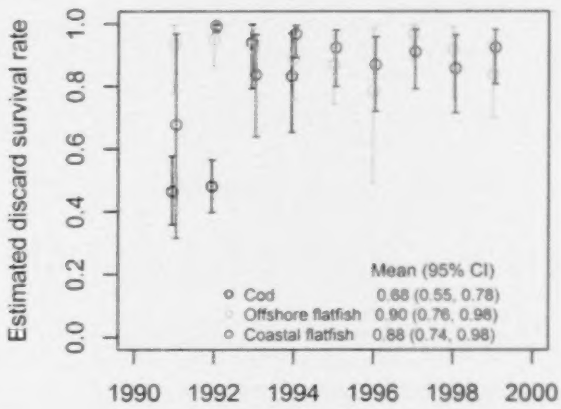

*Figure 34. Annual estimates of Winter Skate discard survival rates (mean and 95% confidence interval) in the main fisheries that catch Winter Skate, 1991 to 1999. The legend indicates the series average and confidence intervals of the survival rates for each fishery.*

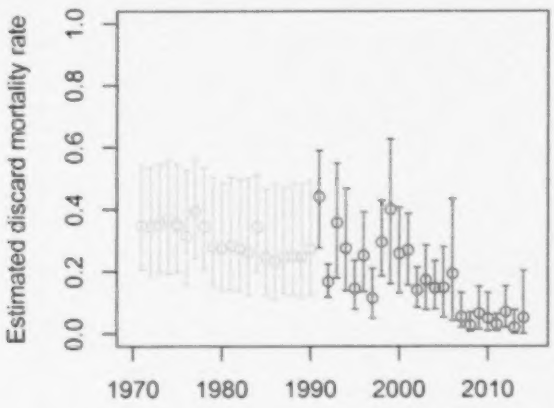

*Figure 35. Estimated Winter Skate discard mortality rate (mean and 95% confidence interval) for groundfish and shrimp fisheries. Blue symbols for the years 191 to 2014 represent estimates derived in large part using annual fisheries observer data (eq. 15), while grey symbols for the years 1971 to 1990 represent estimates derived using mean values for the 1990s (eq. 14).*

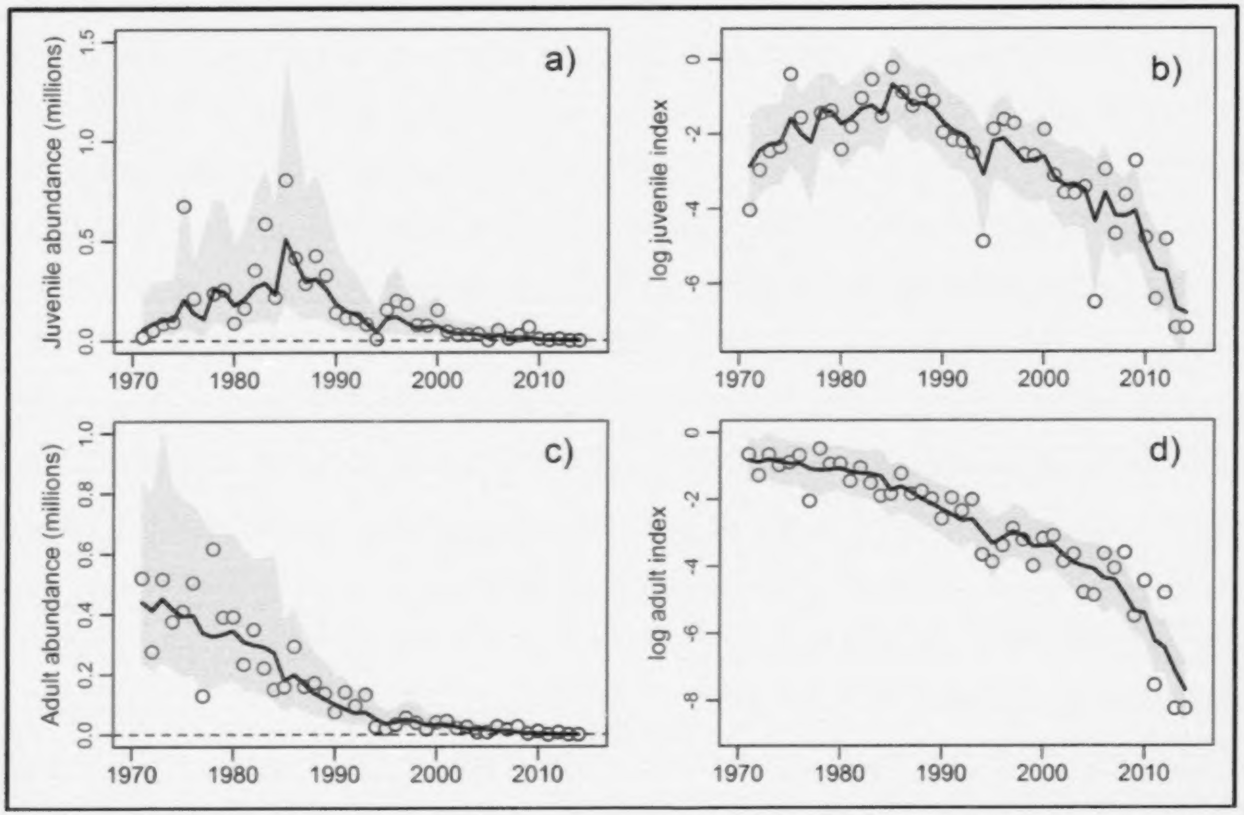

*Figure 36. Relative abundance (trawlable abundance in millions) of juvenile (21 to 41 cm; upper row panels a and b) and adult (≥ 42 cm; lower row panels c and d) Winter Skate in the southern Gulf of St. Lawrence (strata 415 to 439 of the September RV survey). Circles are the observed abundance indices. Lines are the predictions from model Z1. Shading shows the 95% credible limits around the predictions. Panels b and d show the indices with values on the natural log scale.*

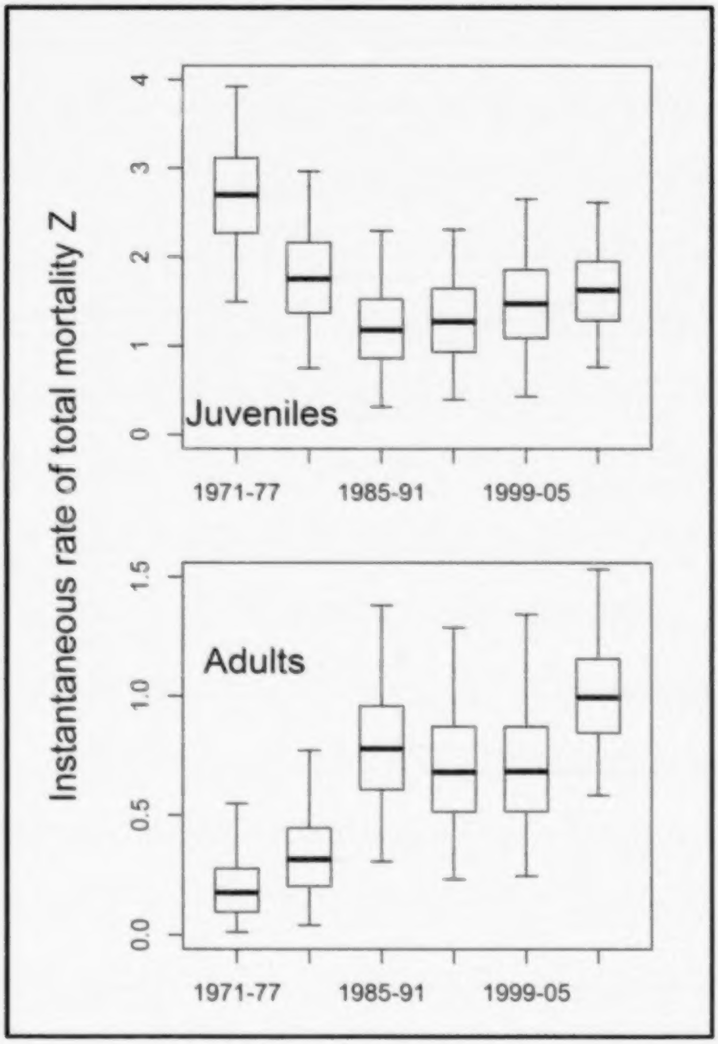

*Figure 37. The instantaneous total mortality rate (Z) of juvenile (21 to 41 cm; upper panel) and adult (≥ 42 cm; lower panel) Winter Skate in the southern Gulf of St. Lawrence, 1971 to 2014, estimated in 7 or 9 year blocks based on Model Z1.*

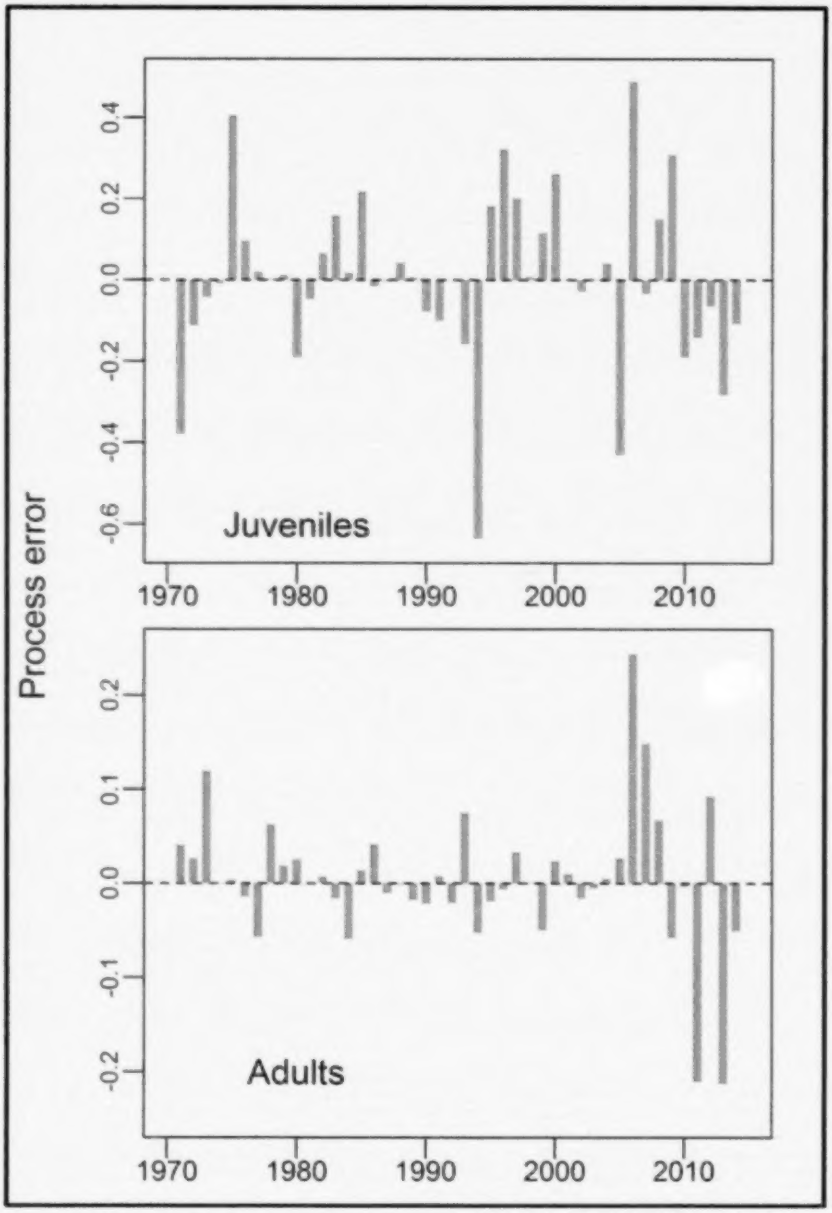

*Figure 38. Process error (log scale) in estimates of juvenile (21 to 41 cm; upper panel) and adult (≥ 42 cm; lower panel) abundance of Winter Skate in the southern Gulf of St. Lawrence, 1971 to 2014, based on Model Z1.*

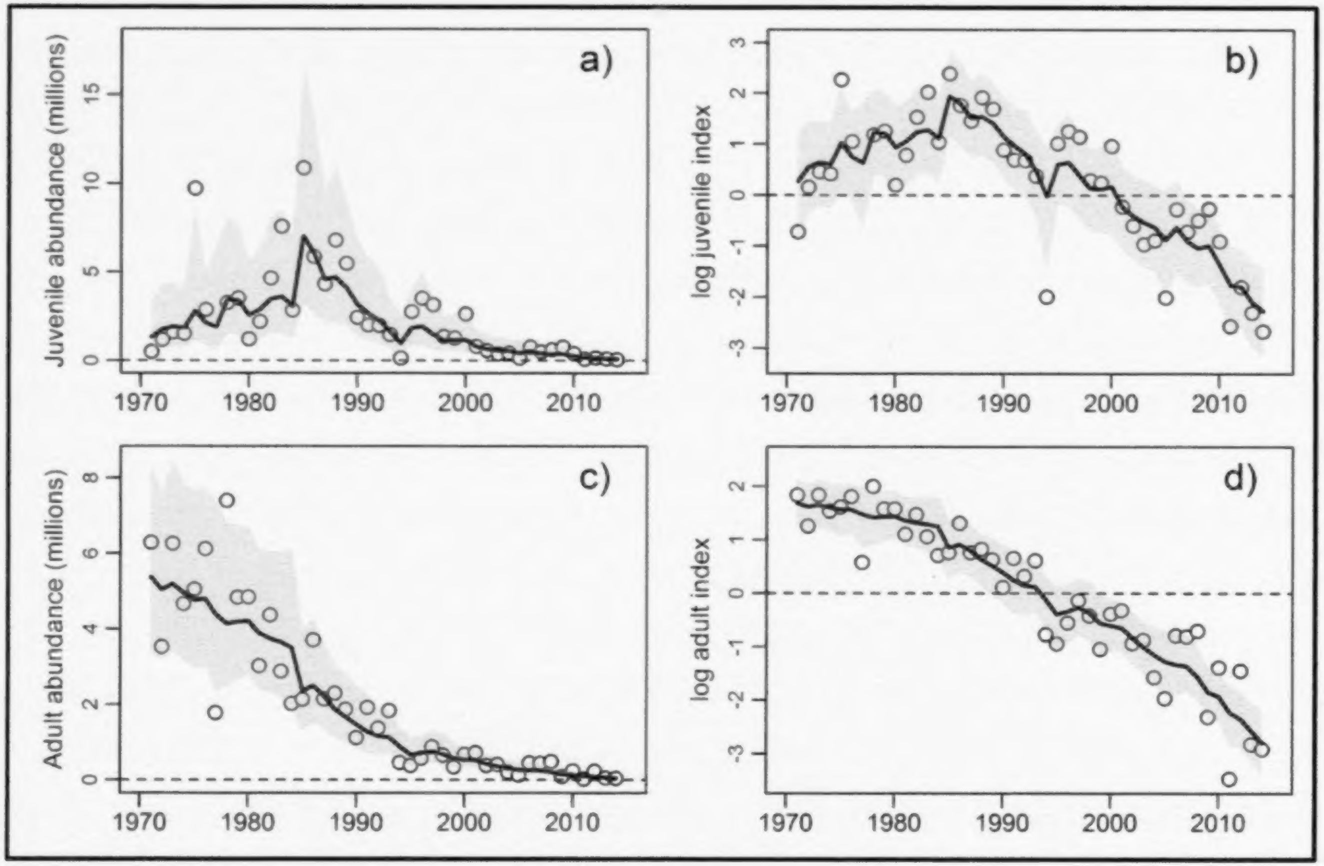

*Figure 39. Relative abundance (trawlable abundance in millions) of juvenile (21 to 41 cm; upper row panel a and b) and adult (≥ 42 cm; lower row panels c and d) Winter Skate in the southern Gulf of St. Lawrence (strata 415 to 439 of the September RV survey, and strata 3 to 5 of the Northumberland Strait survey). Circles are the observed abundance indices. Lines are the predictions from model Z2. Shading shows the 95% credible limits around the predictions. Panels b and d show the abundances on the natural log scale.*

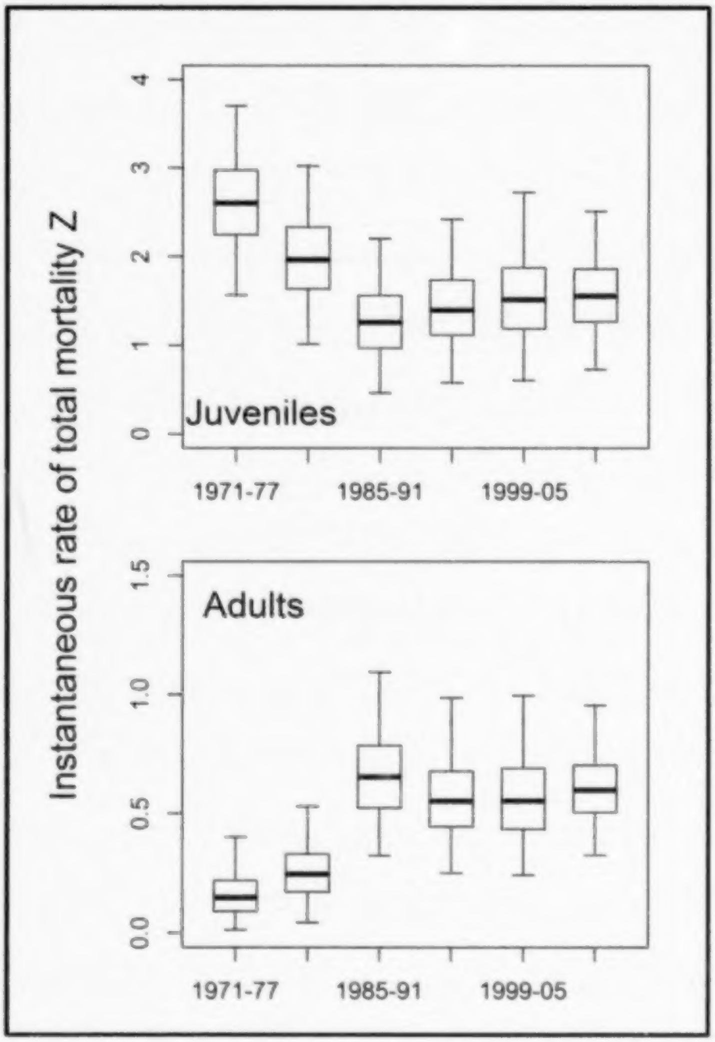

*Figure 40. The instantaneous total mortality rate (Z) of juvenile (21 to 41 cm; upper panel) and adult (≥ 42 cm; lower panel) Winter Skate in the southern Gulf of St. Lawrence, 1971 to 2014, estimated in 7 or 9 year blocks based on Model Z2.*

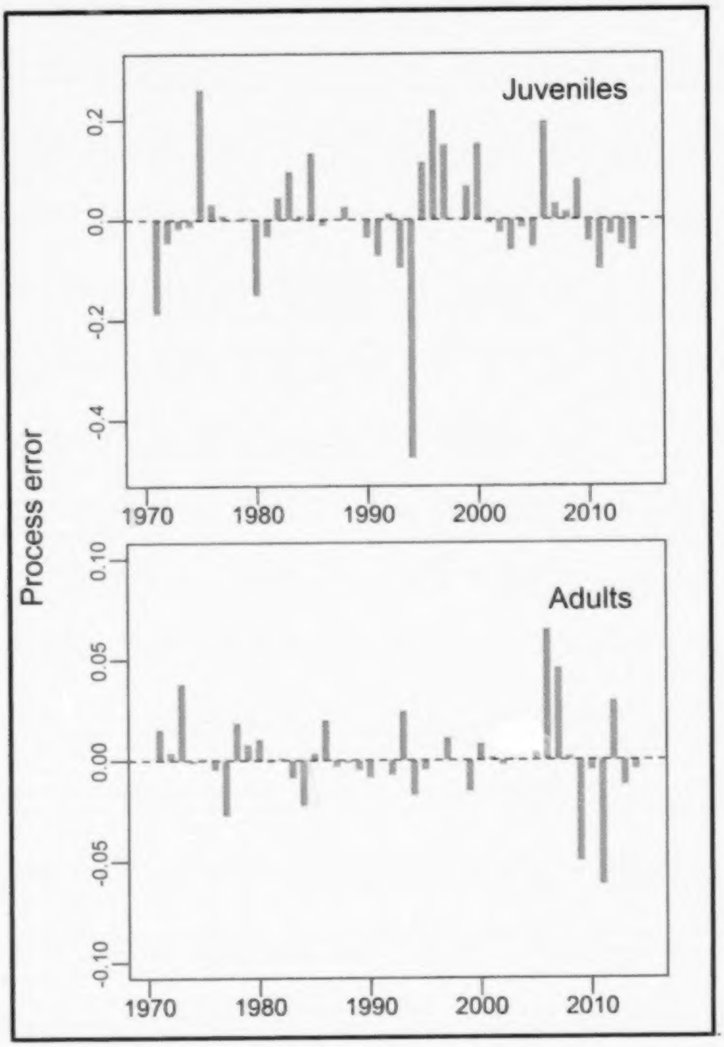

*Figure 41. Process error (log scale) in estimates of juvenile (21 to 41 cm; upper panel) and adult (≥ 42 cm; lower panel) abundance of Winter Skate in the southern Gulf of St. Lawrence, 1971 to 2014, based on Model Z2.*

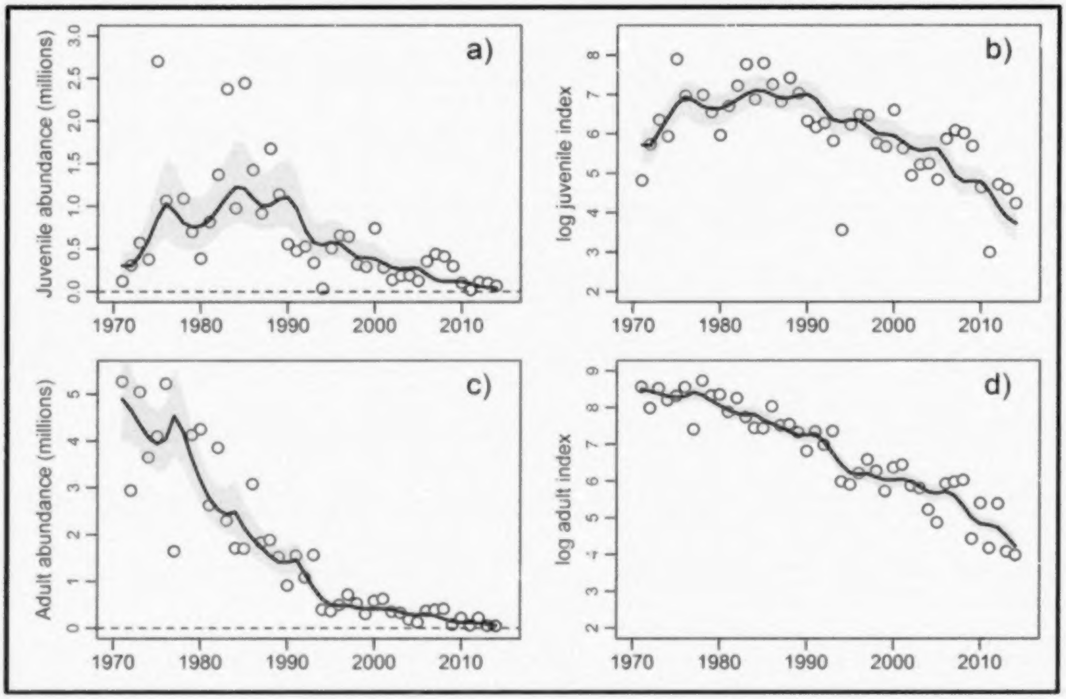

*Figure 42. Fit of the age-structured model to the juvenile (21 to 41 cm; panels a and b) and adult (≥ 42 cm; panels c and d) Winter Skate abundance indices on the arithmetic (panels a and c) and log (panels b and d) scales. Circles are the observed indices and lines and shading show the median and 95% confidence intervals of the predicted values.*

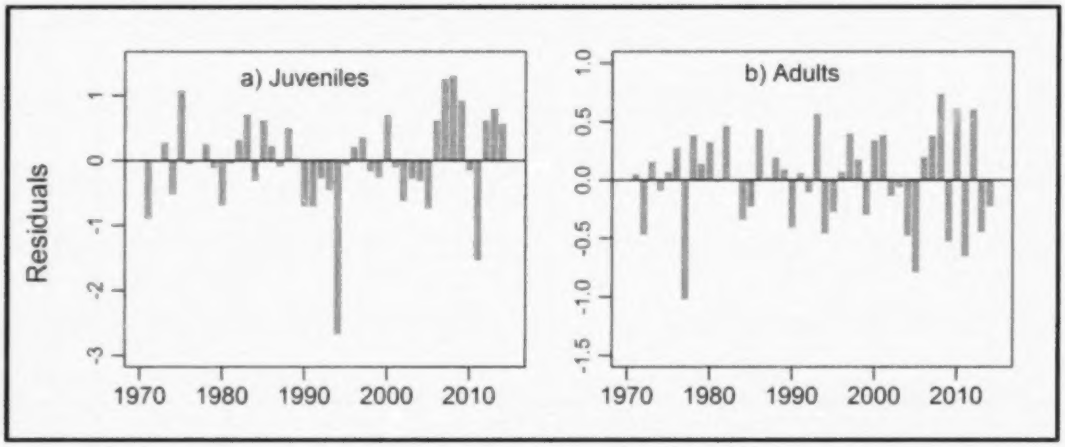

*Figure 43. Residuals between observed and predicted abundance indices (observed-predicted, on the log scale) for juvenile (21 to 41 cm; panel a) and adult (≥42 cm; panel b) Winter Skate, 1971 to 2014.*

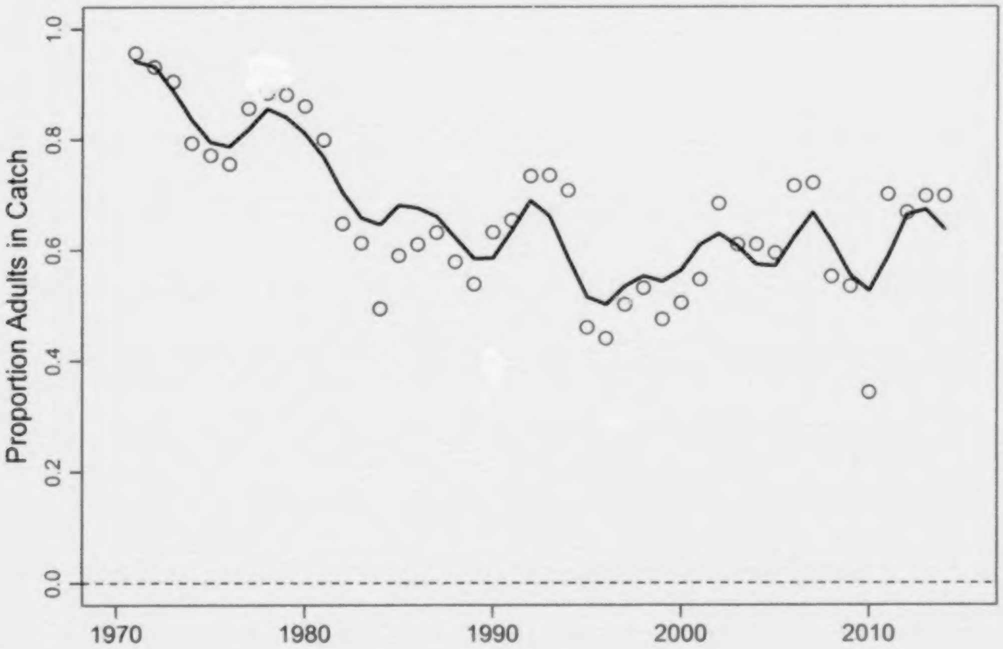

*Figure 44. Observed (circles) and predicted (line) proportion of adult Winter Skate in the fishery catch, 1971 to 2014.*

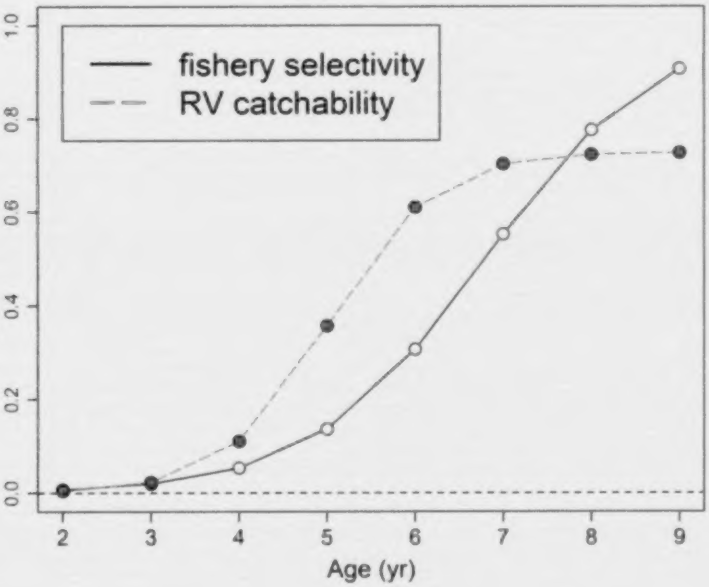

*Figure 45. Estimated selectivity at age to the fishery (solid black line and open circles) and catchability at age to the survey (dashed red line and closed red circles) of Winter Skate by age (year).*

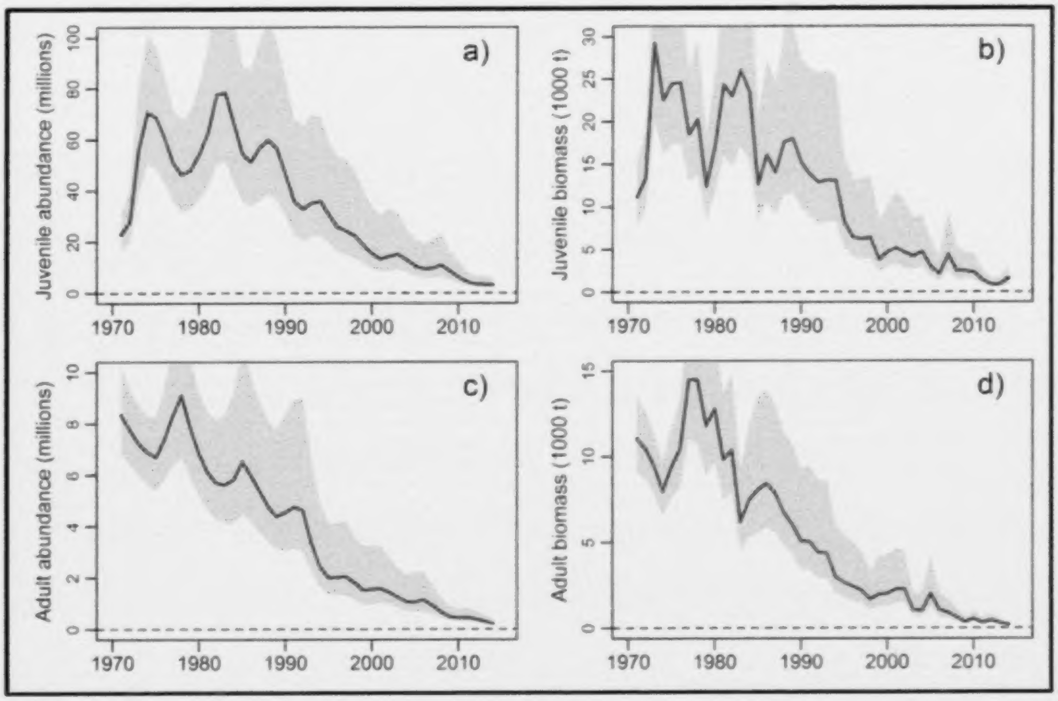

*Figure 46. Estimated abundance (millions; panels a and c) and biomass (1000 t; panels b and d) of juvenile (21 to 41 cm; panels a and b) and adult (≥42 cm; panels c and d) Winter Skate in the southern Gulf of St. Lawrence, 1971 to 2014, based on the age-structured model.*

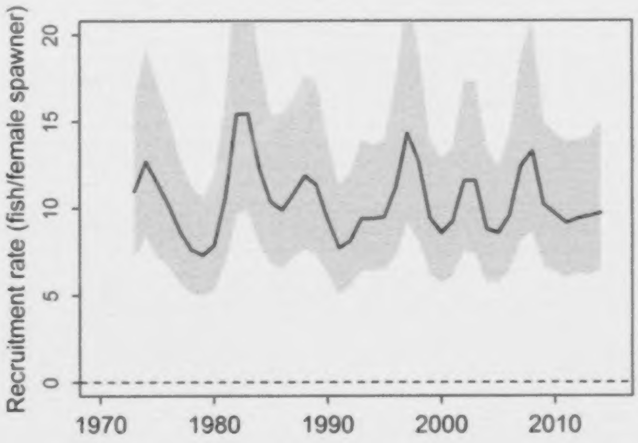

*Figure 47. Estimated recruitment rates of cohorts of Winter Skate in the southern Gulf of St. Lawrence, plotted against year of recruitment at age 2. The median estimates are indicated by the line and their 95% confidence intervals by the shading.*

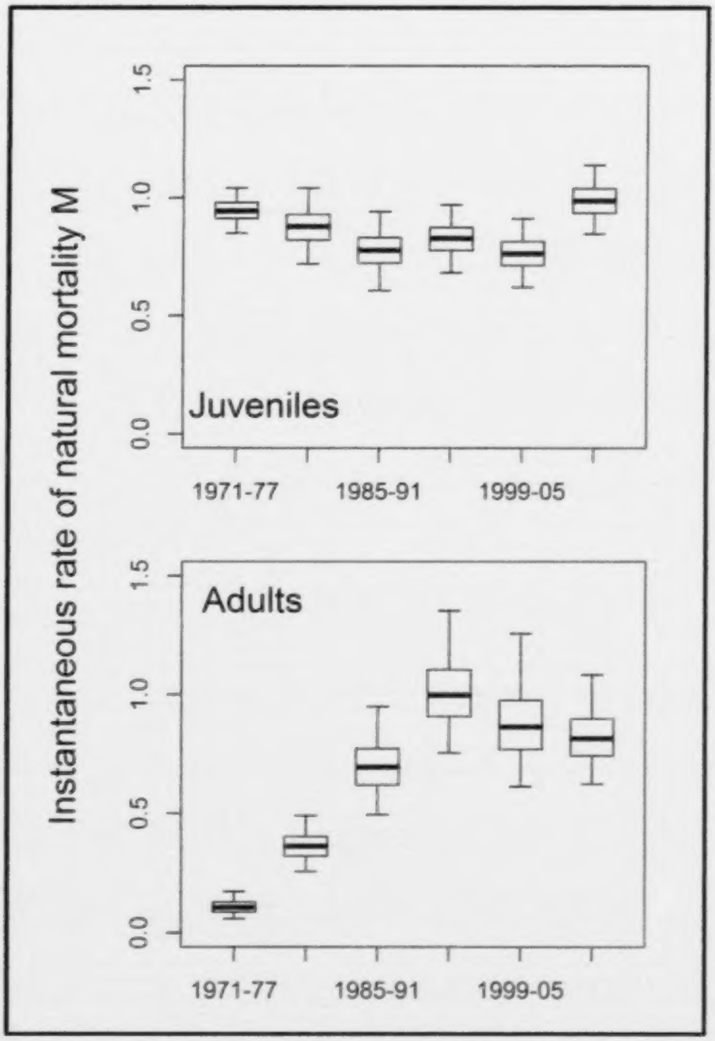

*Figure 48. Estimated instantaneous rates of natural mortality (M) of juvenile (age 2-4 years; panel a) and adult (aged 6+ years; panel b) Winter Skate by time period, 1971 to 2014. Horizontal lines are the median estimates, boxes the 25th to 75th percentiles and vertical lines the 95% confidence intervals. M of 5 year olds was assumed to be the average of the values of M at younger and older ages.*

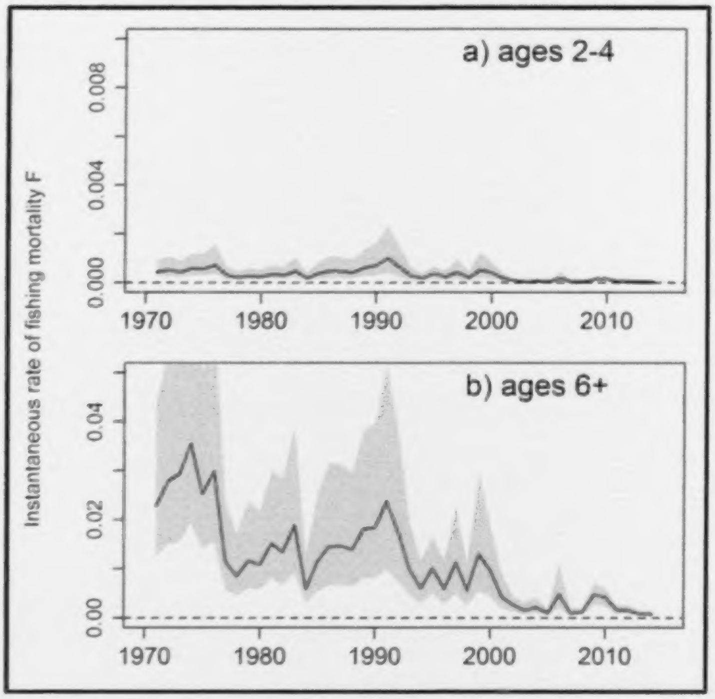

*Figure 49. Estimates of the instantaneous rates of fishing mortality (F) for Winter Skate aged 2 to 4 years (panel a) and aged 6 years and older (lower panel), 1971 to 2014. Lines show the median estimates and shading their 95% confidence intervals.*

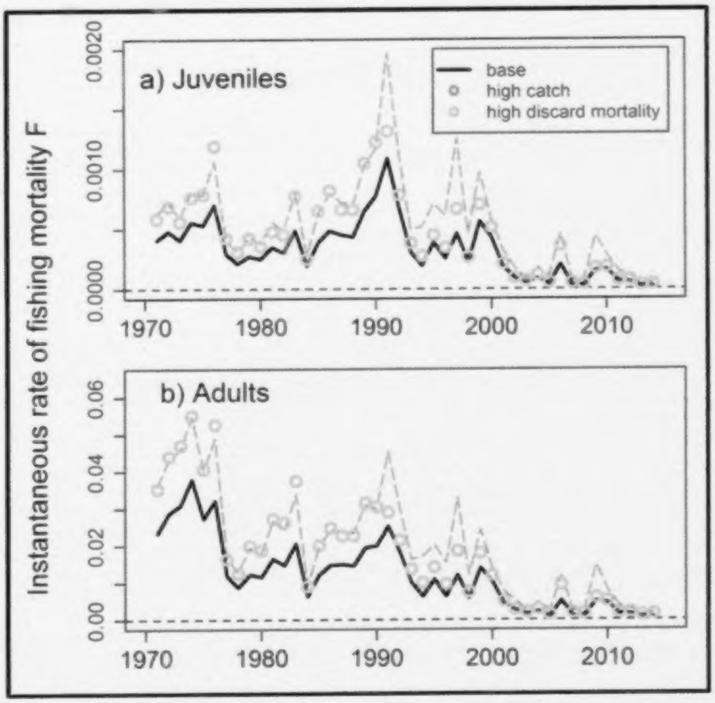

*Figure 50. Estimated fishing mortality rates (F) on juvenile (aged 2 to 4 years; panel a) and adult (aged 6 years and older; panel b) Winter Skate, 1971 to 2014, derived with the base model compared to models with catch set at the 95th percentile of estimated catch or with discard mortality set at a high level (the 95th percentile of estimated discard mortality in the groundfish fishery or 0.187 for the scallop fishery).*

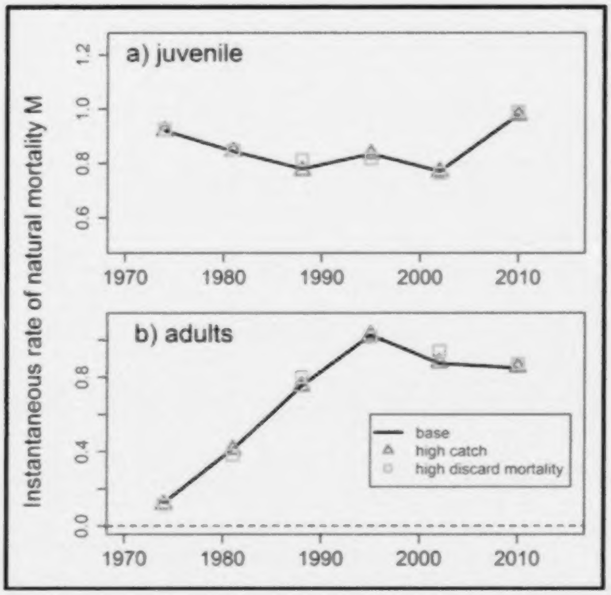

*Figure 51. Estimated natural mortality rates (M) of juvenile (aged 2 to 4 years; panel a) and adult (aged 6 years and older; panel b) Winter Skate, 1971 to 2014, derived with the base model compared to models with catch set at the 95th percentile of estimated catch or with discard mortality set at a high level (the 95th percentile of estimated discard mortality in the groundfish fishery or 0.187 for the scallop fishery).*

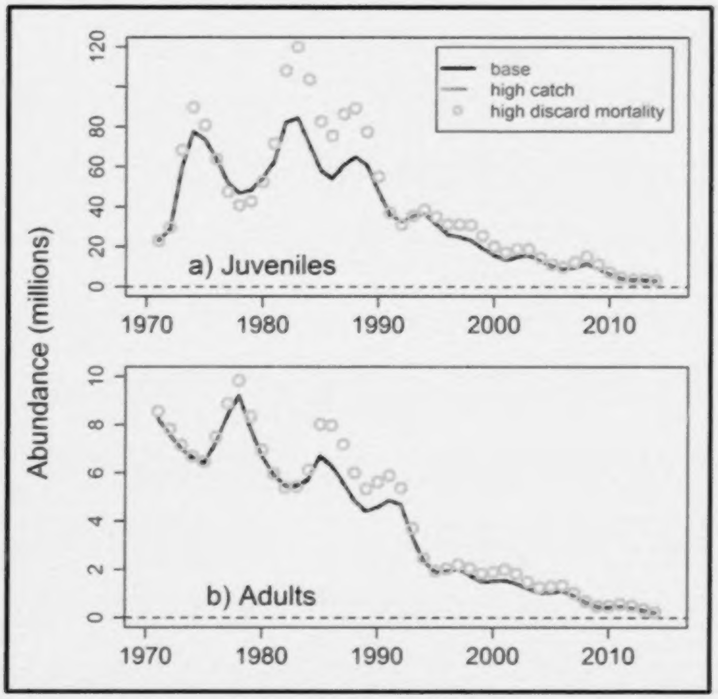

*Figure 52. Estimated abundance (millions) of juvenile (aged 2 to 4 years; panel a) and adult (aged 6 years and older; panel b) Winter Skate, 1971 to 2014, in the base model compared to models with catch set at the 95th percentile of estimated catch or with discard mortality set at a high level (the 95th percentile of estimated discard mortality in the groundfish fishery or 0.187 for the scallop fishery).*

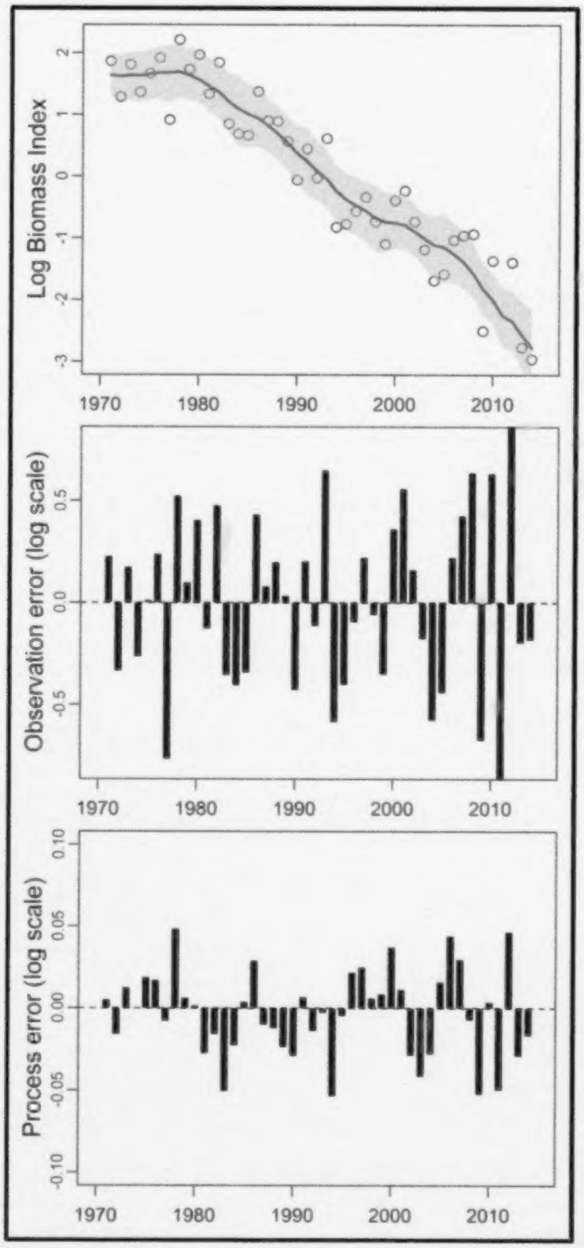

*Figure 53. Model fit for the surplus production model for Winter Skate from the southern Gulf of St. Lawrence, 1971 to 2014. Top panel: biomass index with observed (circles) and predicted values of the biomass index. Line shows the median prediction and shading its 95% confidence interval. Middle panel: observation residuals (observed-predicted). Bottom panel: process error deviates (observed-predicted).*

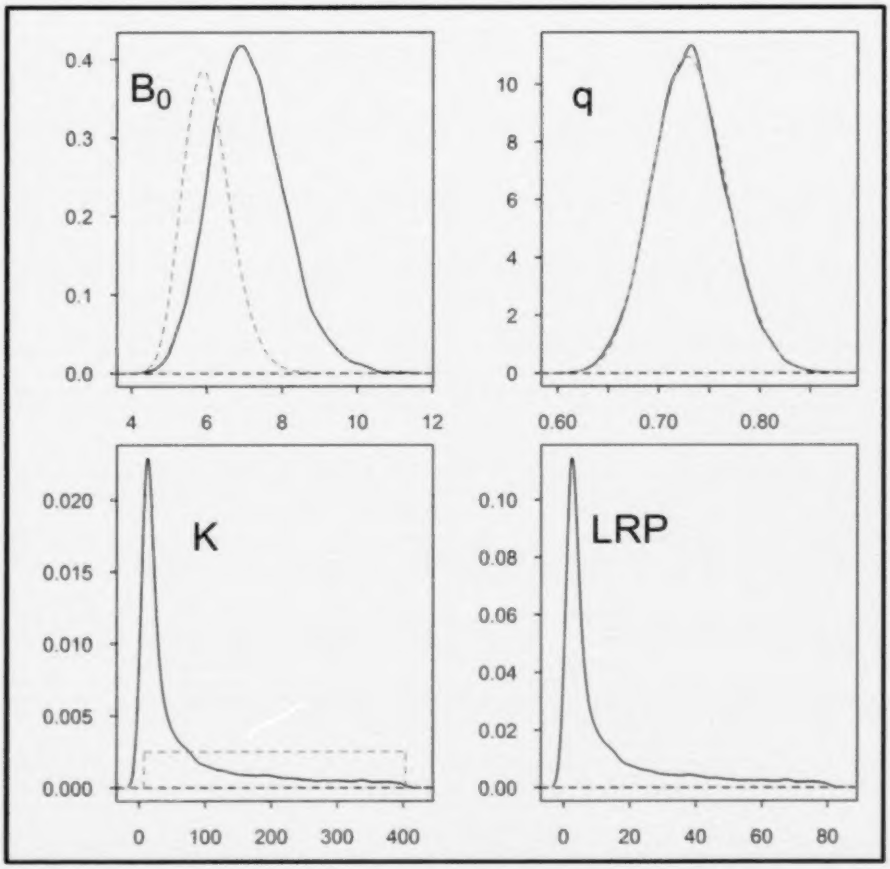

*Figure 54. Prior (red dashed line) and posterior (solid black line) distributions for selected parameters of the surplus production model for Winter Skate from the southern Gulf of St. Lawrence. B0 is the adult biomass in 1970, q is the catchability to the survey, K is the carrying capacity and LRP is the limit reference point which is derived variable from the other parameters.*

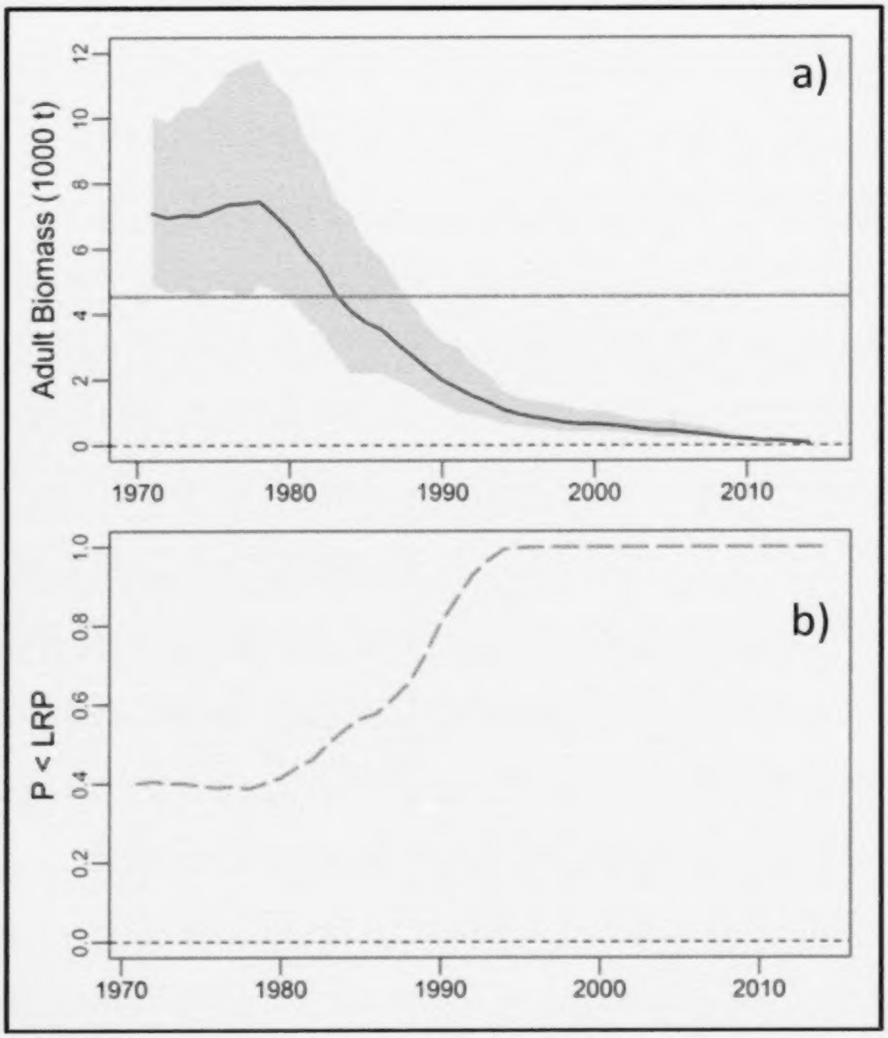

*Figure 55. Adult biomass (1000 t; panel a) and probability that the estimated biomass is below the limit reference point (panel b), based on the surplus production model for Winter Skate from the southern Gulf of St. Lawrence, 1971 to 2014. In panel a, the black line is the median estimate of adult biomass, the shading its 95% confidence interval and the horizontal red line median estimate of the LRP (40% of $B_{MSY}$).*

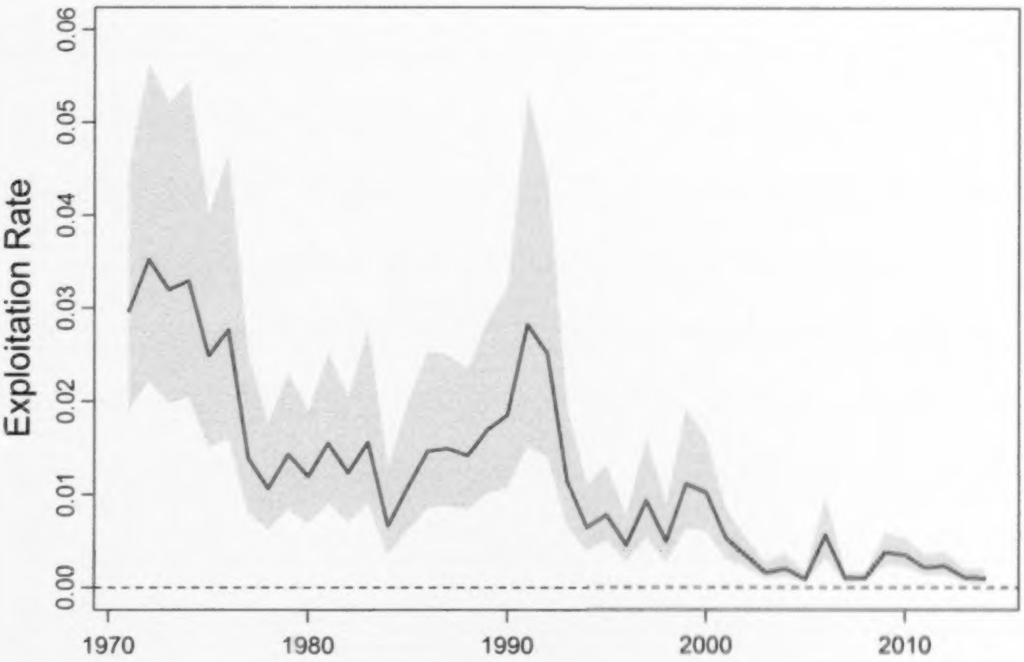

*Figure 56. Estimates of the exploitation rate of adult Winter Skate from the southern Gulf of St. Lawrence, 1971 to 2014, based on a surplus production model. Lines show the median estimates and shading their 95% confidence intervals.*

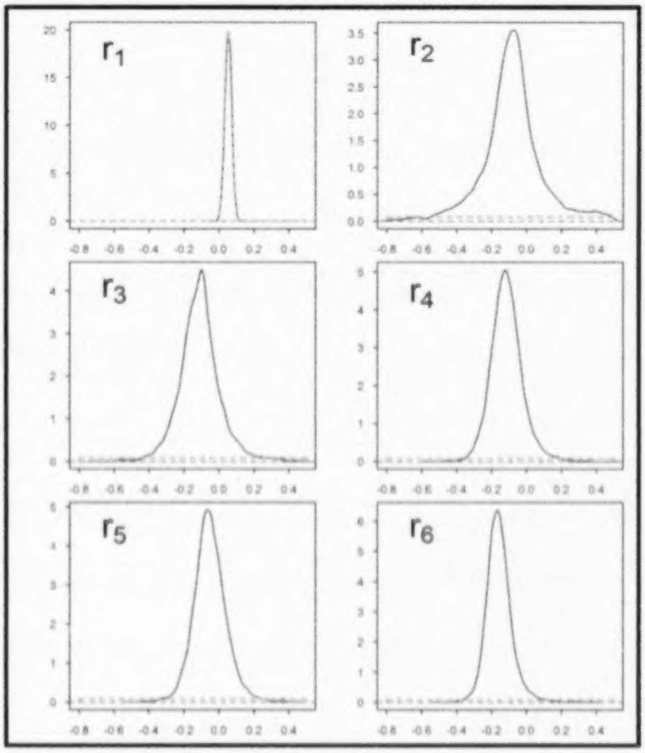

*Figure 57. Prior (red dashed lines) and posterior (black solid lines) distributions of r, the intrinsic rate of population increase in the surplus production model of Winter Skate from the southern Gulf of St. Lawrence for six time periods: 1) 1971 to 1977, 2) 1978 to 1984, 3) 1985 to 991, 4) 1992 to 1998, 5) 1999 to 2005, and 6) 2006 to 2014.*

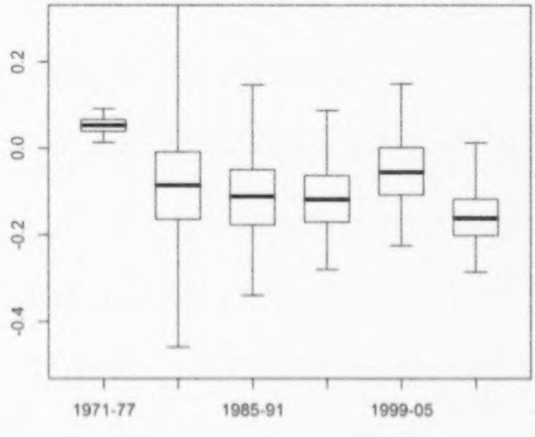

*Figure 58. Box plots of the posterior distributions of r, the intrinsic rate of population increase, in the surplus production model of Winter Skate from the southern Gulf of St. Lawrence, for six time periods. Horizontal lines show the medians, boxes the inter-quartile range (25th to 75th percentiles), and vertical lines the 95% confidence intervals.*

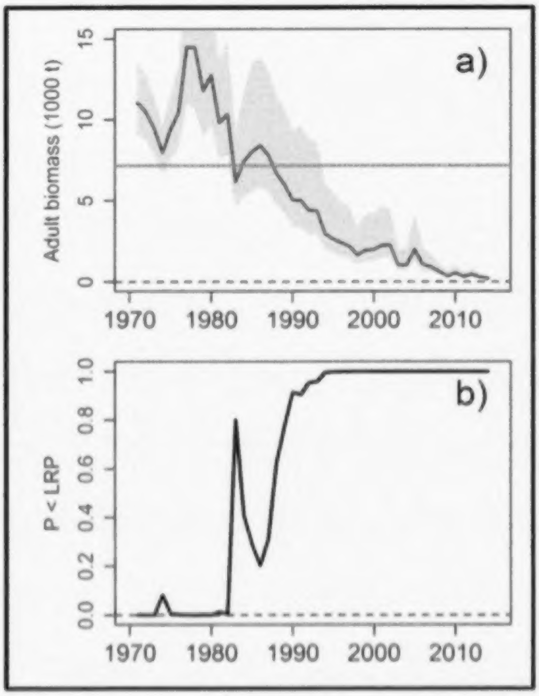

*Figure 59. Adult biomass (1000 t; panel a) estimated by the age-structured model and the probability that it is below the limit reference point (panel b) estimated by the surplus production model and expressed as a proportion (0.6481) of biomass in 1971 for Winter Skate of the southern Gulf of St. Lawrence. In panel a, the black line is the median estimate of adult biomass, the shading its 95% confidence interval and the horizontal red line median estimate of the LRP.*

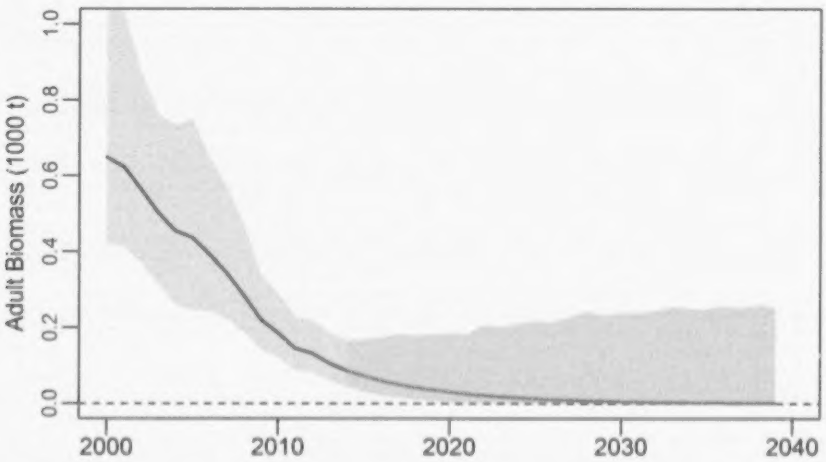

*Figure 60. A 25-year projection of adult biomass of Winter Skate from the southern Gulf of St. Lawrence based on the surplus production model assuming that the current productivity conditions were to persist during the projection (i.e., r remains at the 2006 to 2014 level). Lines show the median estimate and shading the 95% confidence interval. Black line denotes observed years and red denotes projection years.*

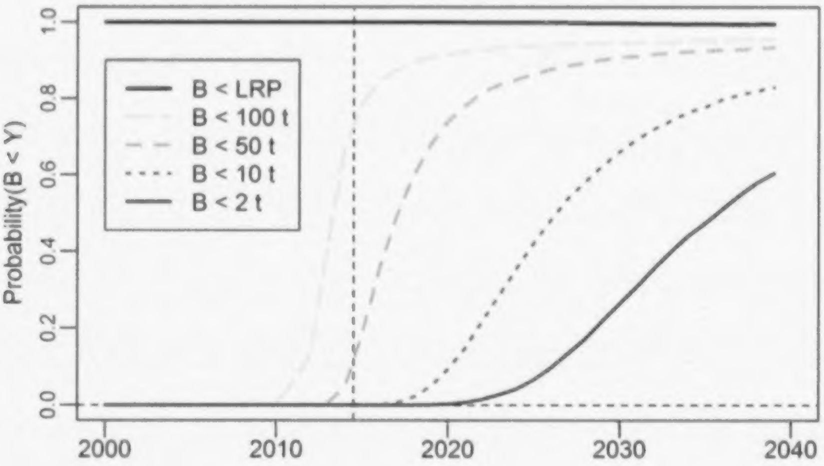

*Figure 61. Probability that adult biomass of Winter Skate from the southern Gulf of St. Lawrence is estimated to be below various levels (LRP, 100 t, 50 t, 10 t or 2 t) during the projection period based on the surplus production model.*

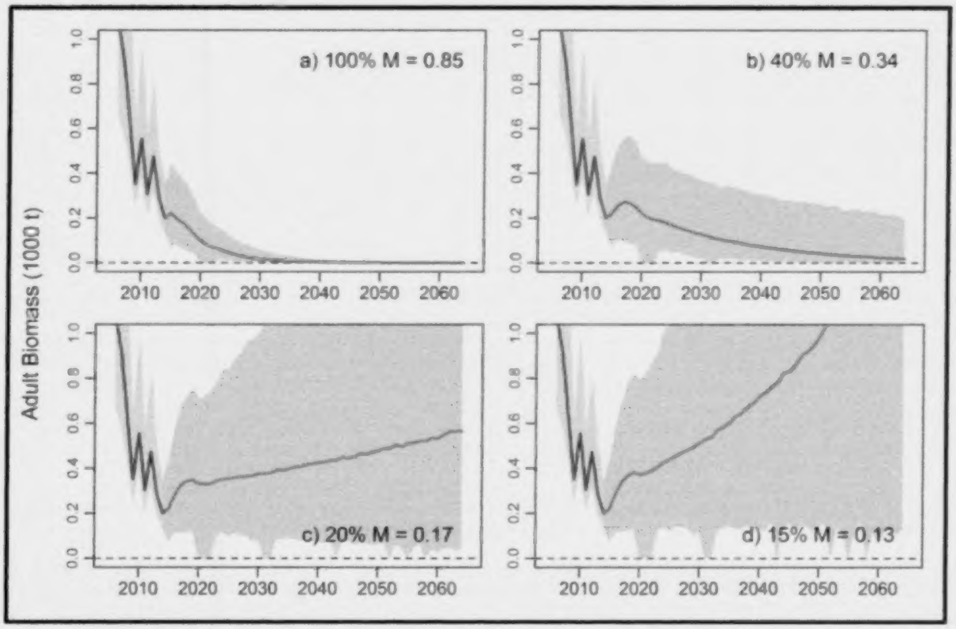

*Figure 62. A 50-year projection of adult biomass of Winter Skate from the southern Gulf of St. Lawrence based on the age-structured model assuming that productivity conditions remain at the current level (panel a) or increase to higher levels (panels b to d). Productivity changes reflect changes in adult natural mortality (M). Lines show the median estimate and shading the 95% confidence interval. Black line denotes observed years and red denotes projection years.*

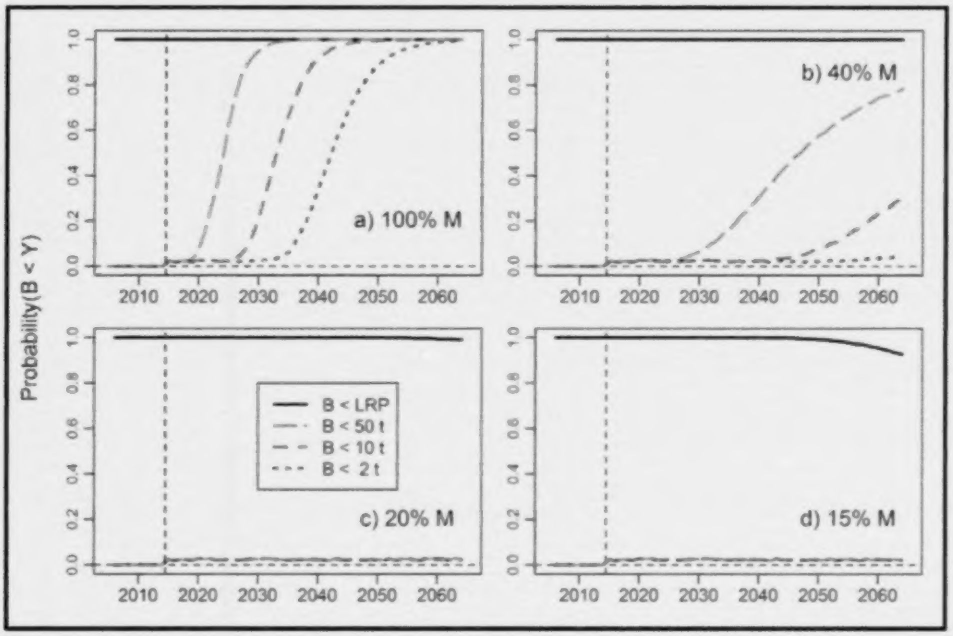

*Figure 63. Probability that adult biomass of Winter Skate of the southern Gulf of St. Lawrence is estimated to be below various levels (LRP, 50 t, 10 t or 2 t) during the projection period based on the age structured model.*

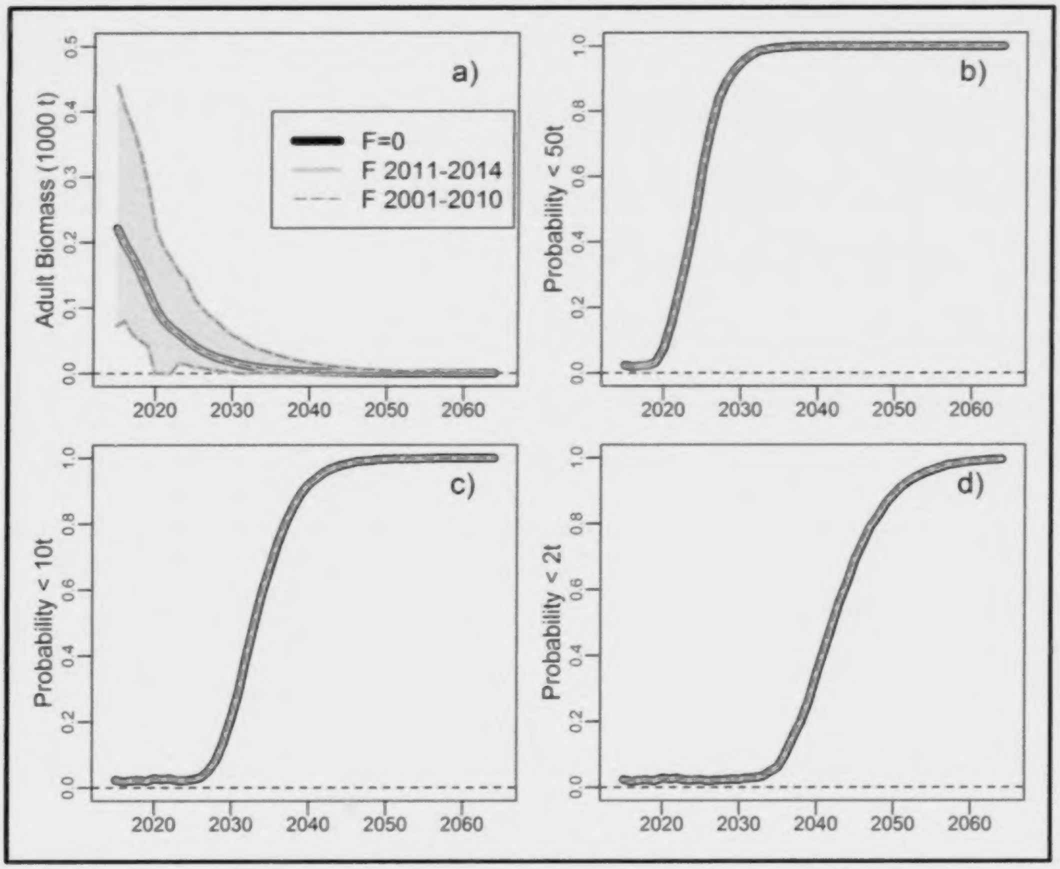

*Figure 64. Projected adult biomass (1000 t; panel a) of Winter Skate from the southern Gulf of St. Lawrence and probabilities of the annual biomass being < 50 t (panel b), < 10 t (panel c) and < 2 t (panel d) with no fishery removals (thick black line) or with the instantaneous rate of fishing mortality (F) set at the average value during 2011 to 2014 (solid yellow line) or 2001 to 2010 (red dashed line). F averaged 0.003 and 0.0001 for adults and juveniles in 2001 to 2010 and 0.001 and 0.00004 in 2011 to 2014, respectively. Heavy lines show the median estimates and grey shading or thin lines the 95% confidence intervals.*

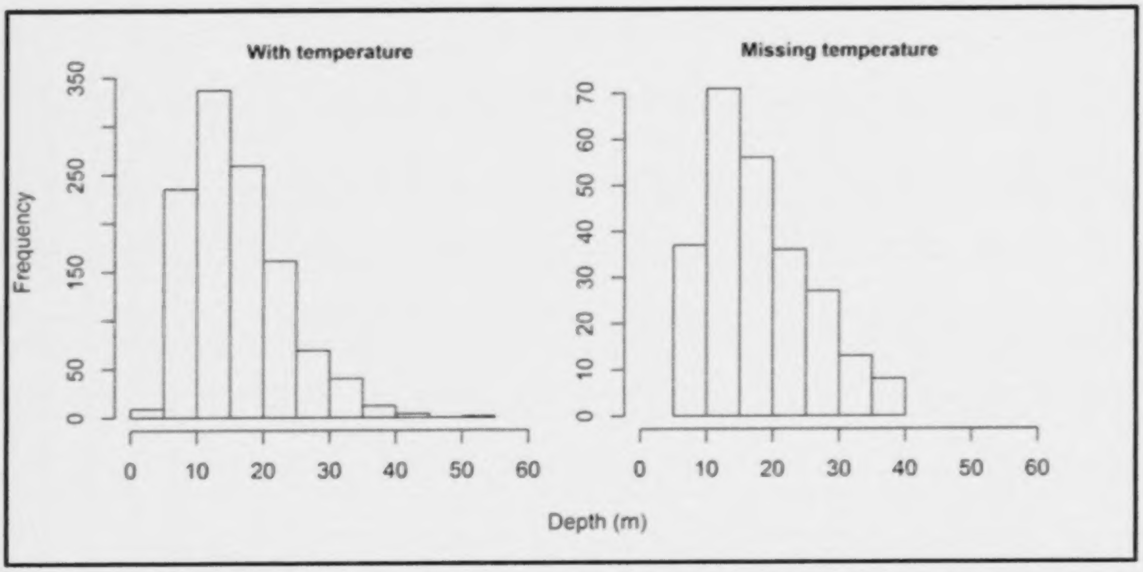

*Figure 65. Frequency distributions of depths for tows in the NS survey with (left panel) and without (right panel) bottom temperature values.*

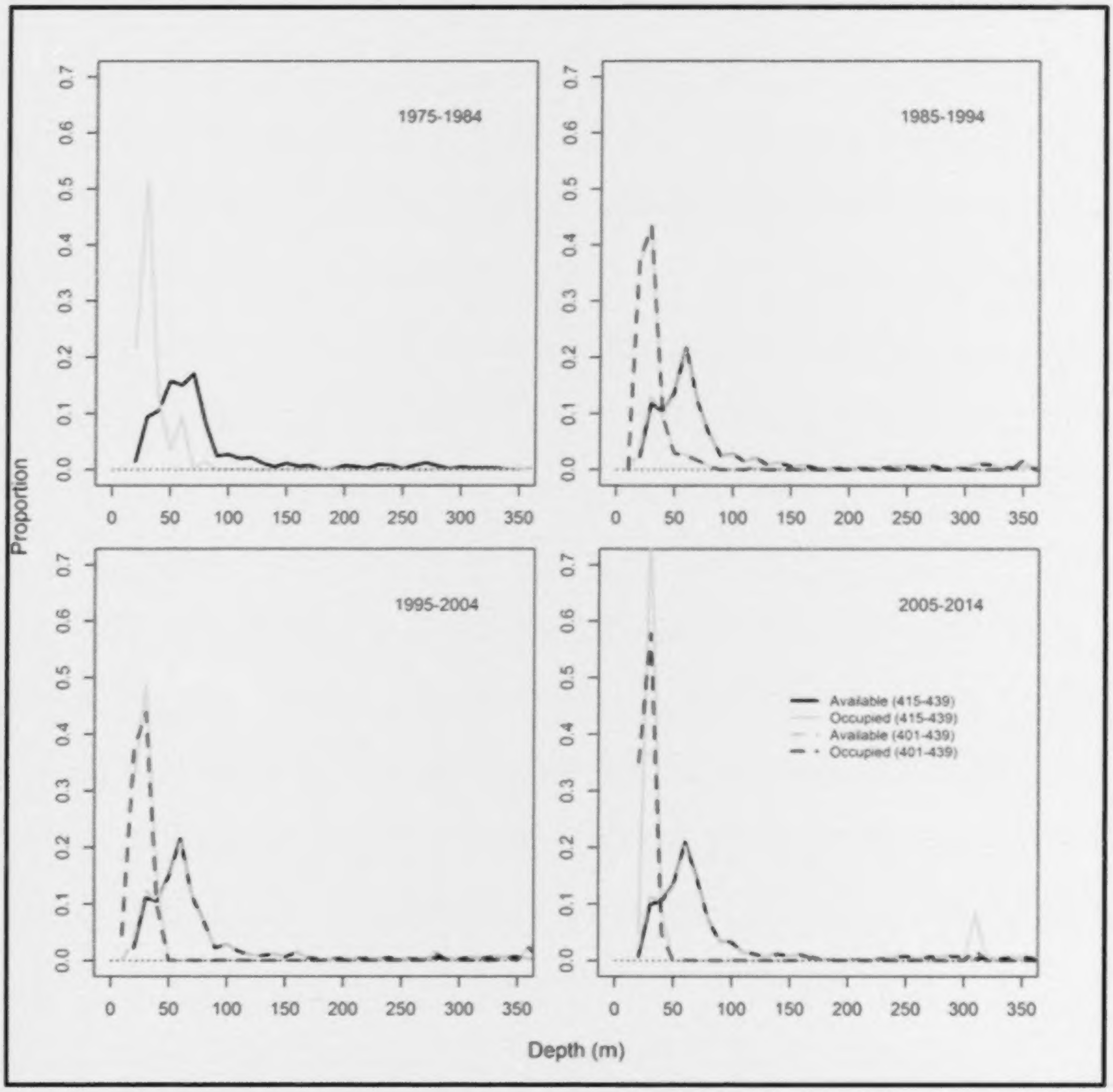

*Figure 66. Proportional distributions of the survey area (black and grey lines) and of juvenile Winter Skate abundance (light and dark blue lines) at depths by decadal block for the RV survey based on strata 415 to 439 (solid lines) and strata 401 to 439 (dashed lines).*

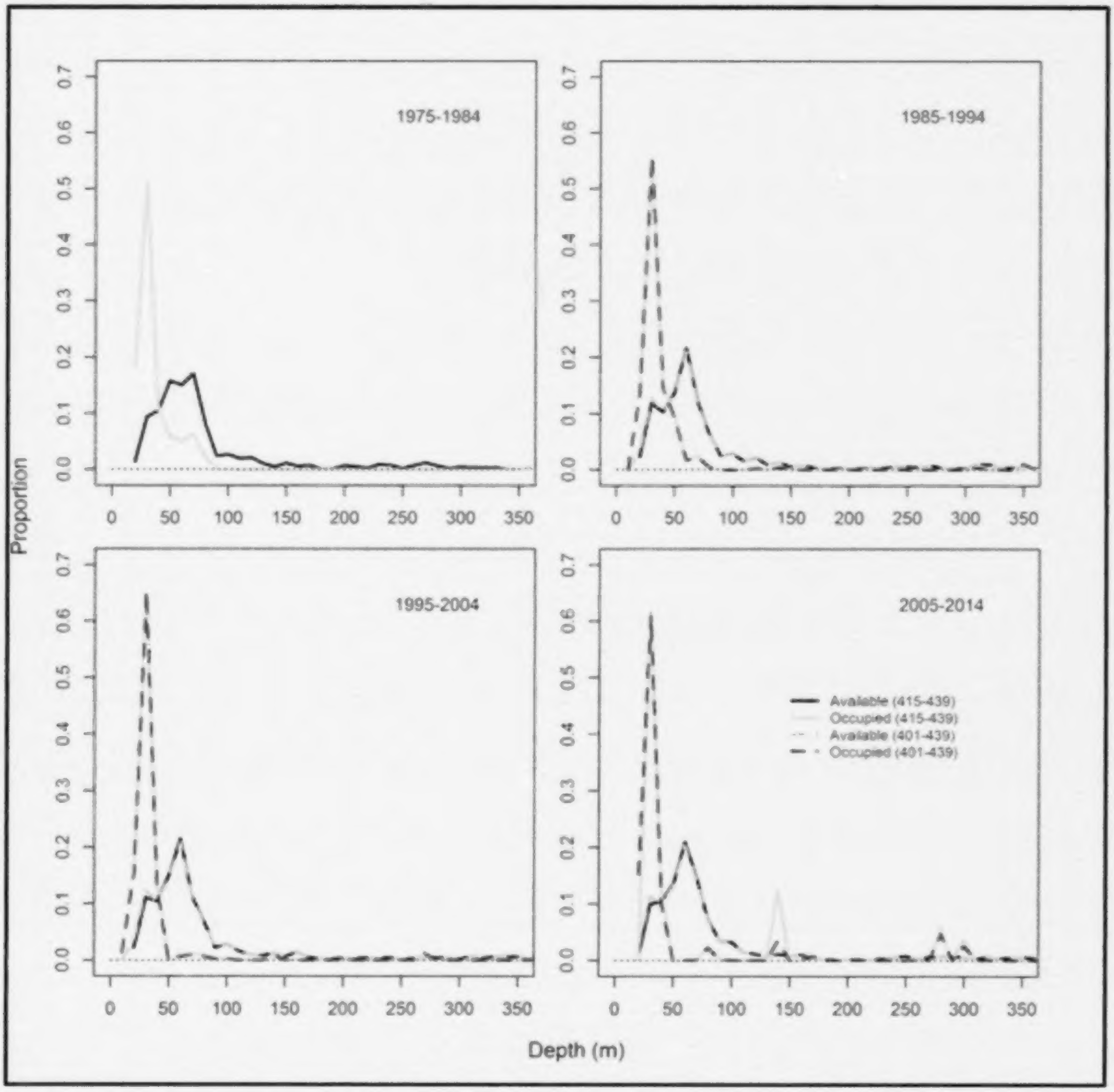

*Figure 67. Proportional distributions of the survey area (black and grey lines) and of adult Winter Skate abundance (light and dark blue lines) at depths by decadal block for the RV survey based on strata 415 to 439 (solid lines) and strata 401 to 439 (dashed lines).*

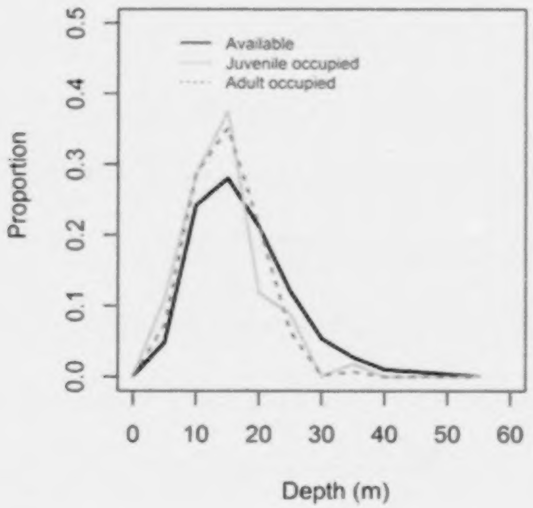

*Figure 68. Proportional distribution of the survey area (black line) and of juvenile (orange solid line) and adult (dashed red line) Winter Skate abundance by depth in the NS survey, 2003 to 2014.*

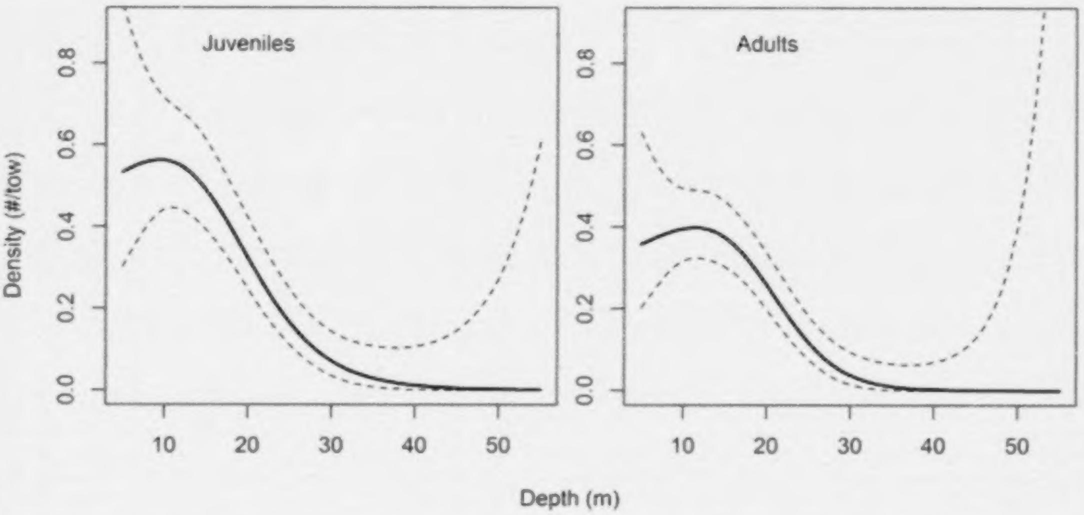

*Figure 69. Predicted density (number per tow) of juvenile (left panel) and adult (right panel) Winter Skate as a function of depth in the NS survey based on generalized additive models. The dashed lines are the 95% confidence interval for the prediction.*

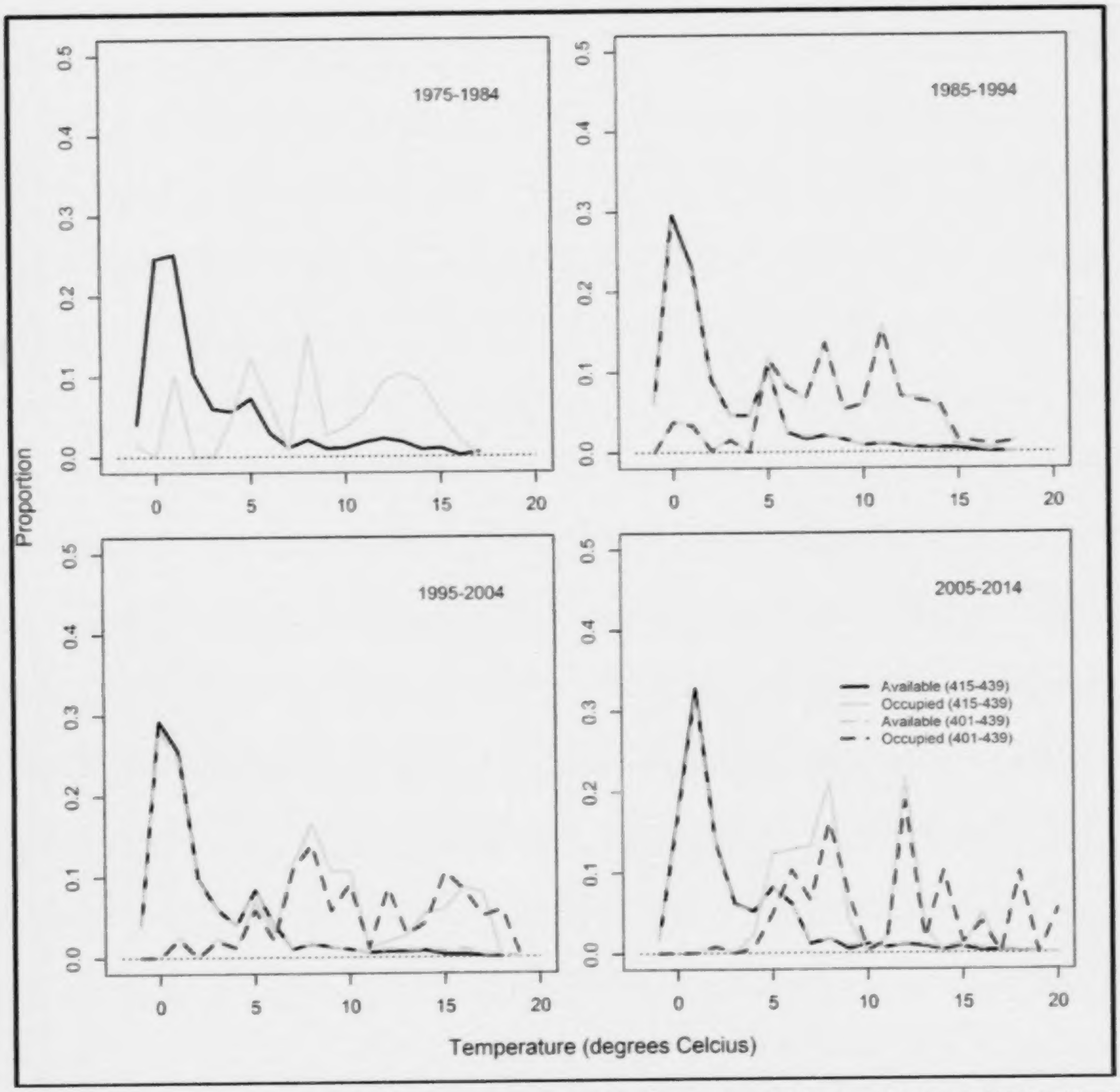

*Figure 70. Proportional distributions of the survey area (black and grey lines) and of juvenile Winter Skate abundance (light and dark blue lines) by bottom temperature bins and by decadal block for the RV survey based on strata 415 to 439 (solid lines) and strata 401 to 439 (dashed lines).*

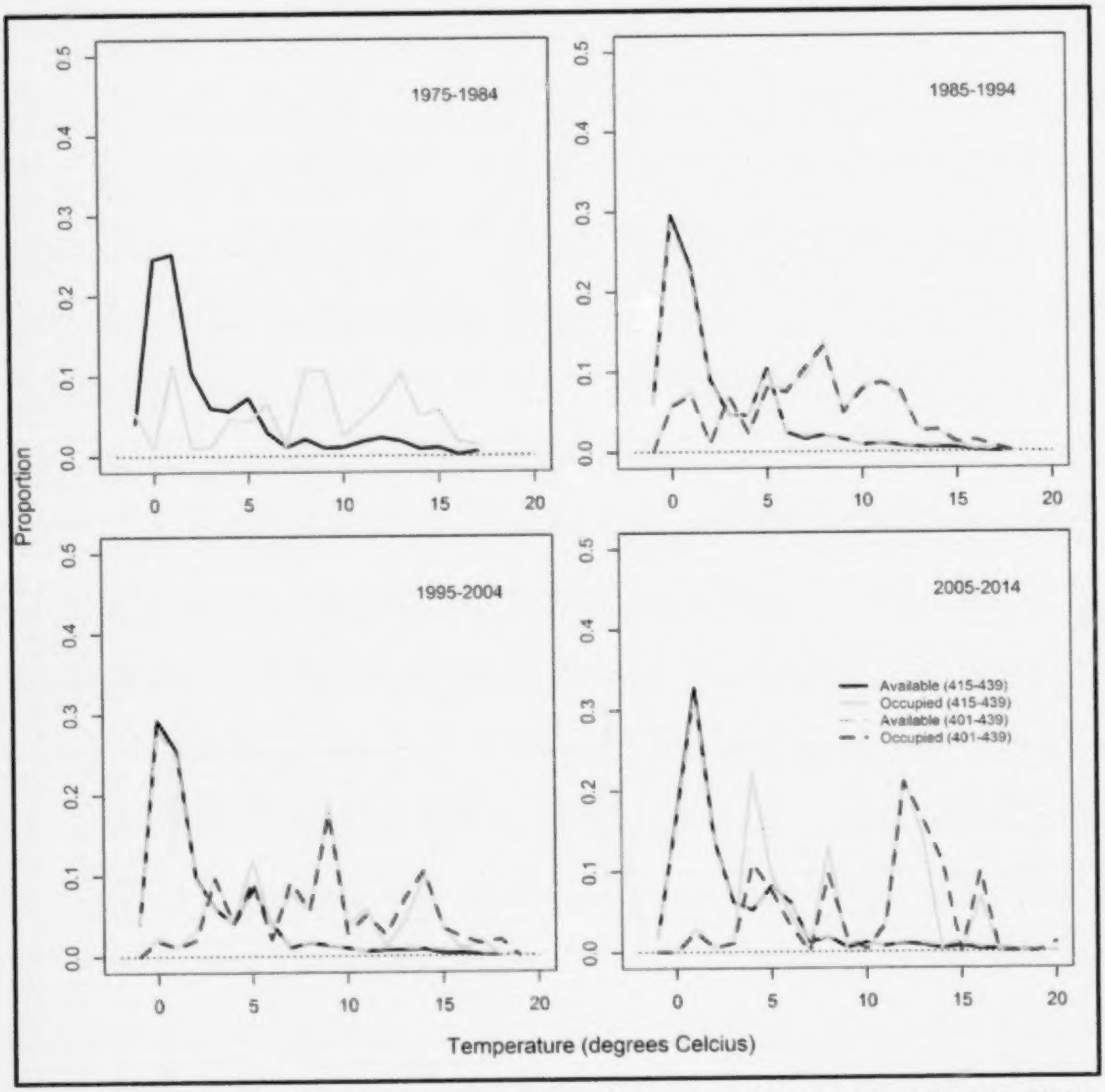

*Figure 71. Proportional distributions of the survey area (black and grey lines) and of adult Winter Skate abundance (light and dark blue lines) by bottom temperature bins and by decadal block for the RV survey based on strata 415 to 439 (solid lines) and strata 401 to 439 (dashed lines).*

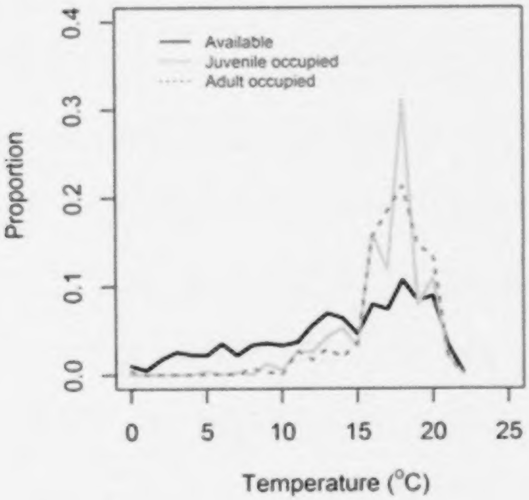

*Figure 72. Proportional distribution of the survey area (black line) and of juvenile (orange solid line) and adult (dashed red line) Winter Skate abundance by bottom temperature bins in the NS survey, 2003 to 2014.*

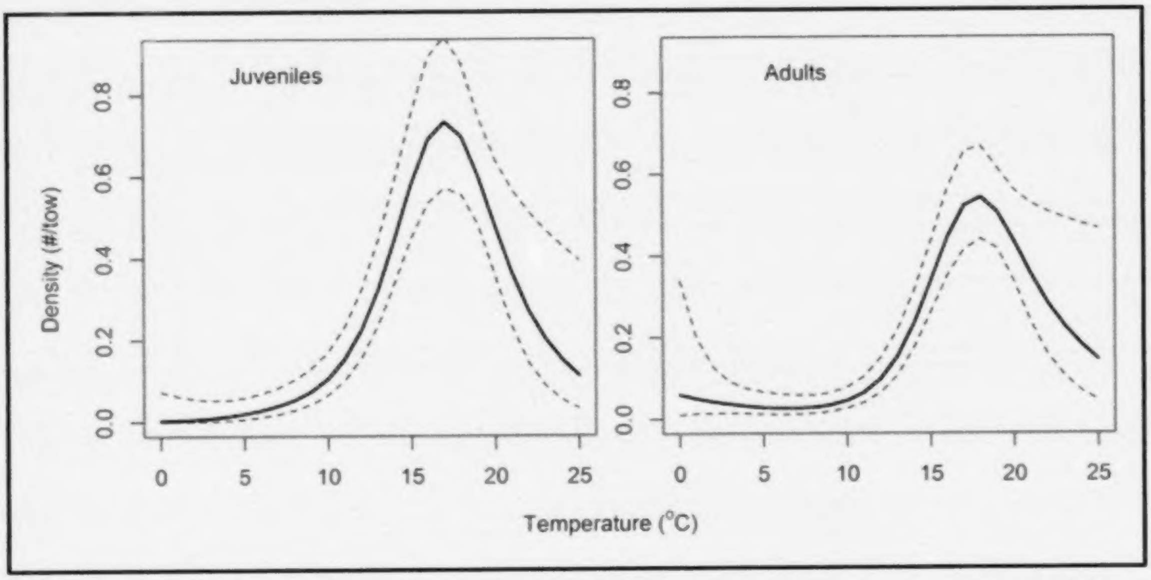

*Figure 73. Predicted density (number per tow) of juvenile (left panel) and adult (right panel) Winter Skate as a function of bottom temperature in the NS survey based on generalized additive models. The dashed lines are the 95% confidence interval for the prediction.*

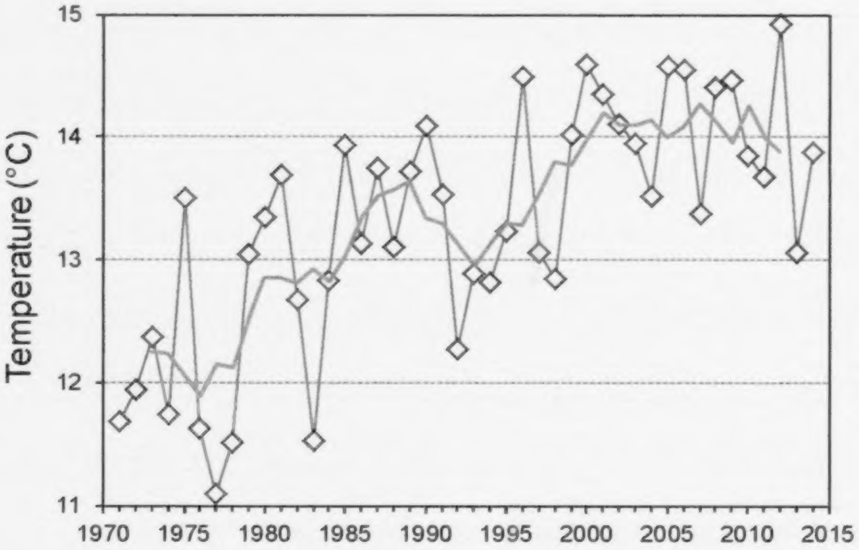

*Figure 74. Index of bottom temperatures in September in coastal regions (depth ≤ 50 m) of the southern Gulf of St. Lawrence, 1971 to 2014. The heavy line is the 5-year running mean.*

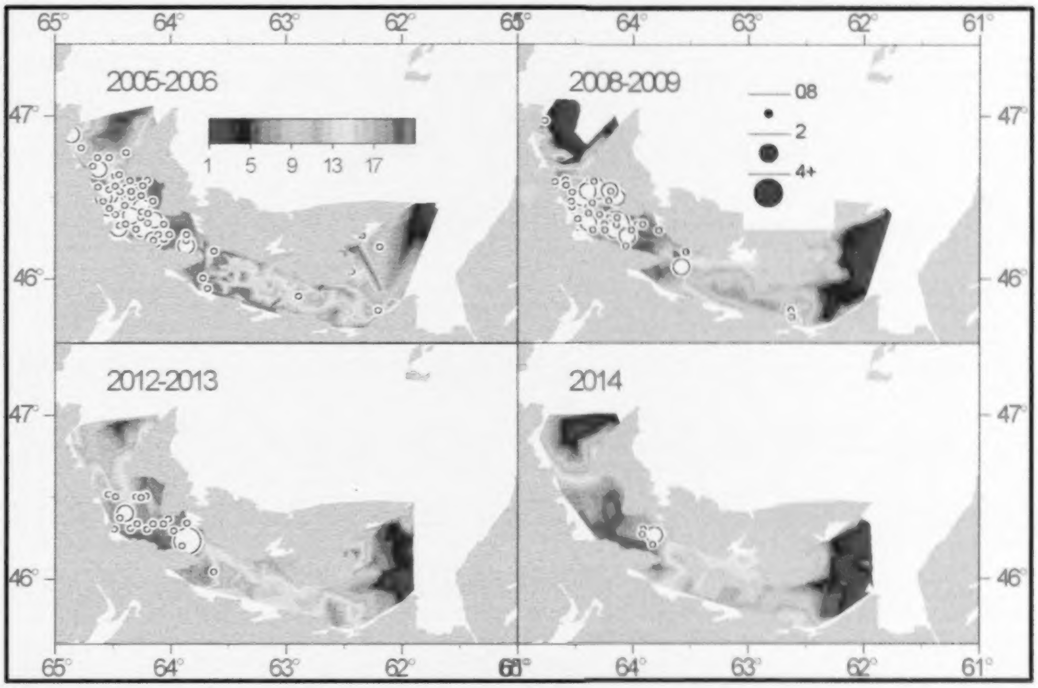
2005-2006
2008-2009
2012-2013
2014
1
5
9
13
17
08
2
4+
65°
64°
63°
62°
61°
47°
46°

*Figure 75. Catches of adult Winter Skate in the Northumberland Strait survey (circles) in relation to bottom water temperature (shading). Circles are proportional to numbers caught.*

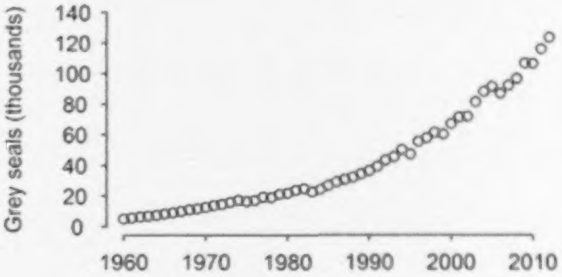

*Figure76. Estimated abundance of Grey Seal foraging in the southern Gulf of St. Lawrence and the Cabot Strait (from Swain et al. 2015, using data from Hammill et al. 2014a).*

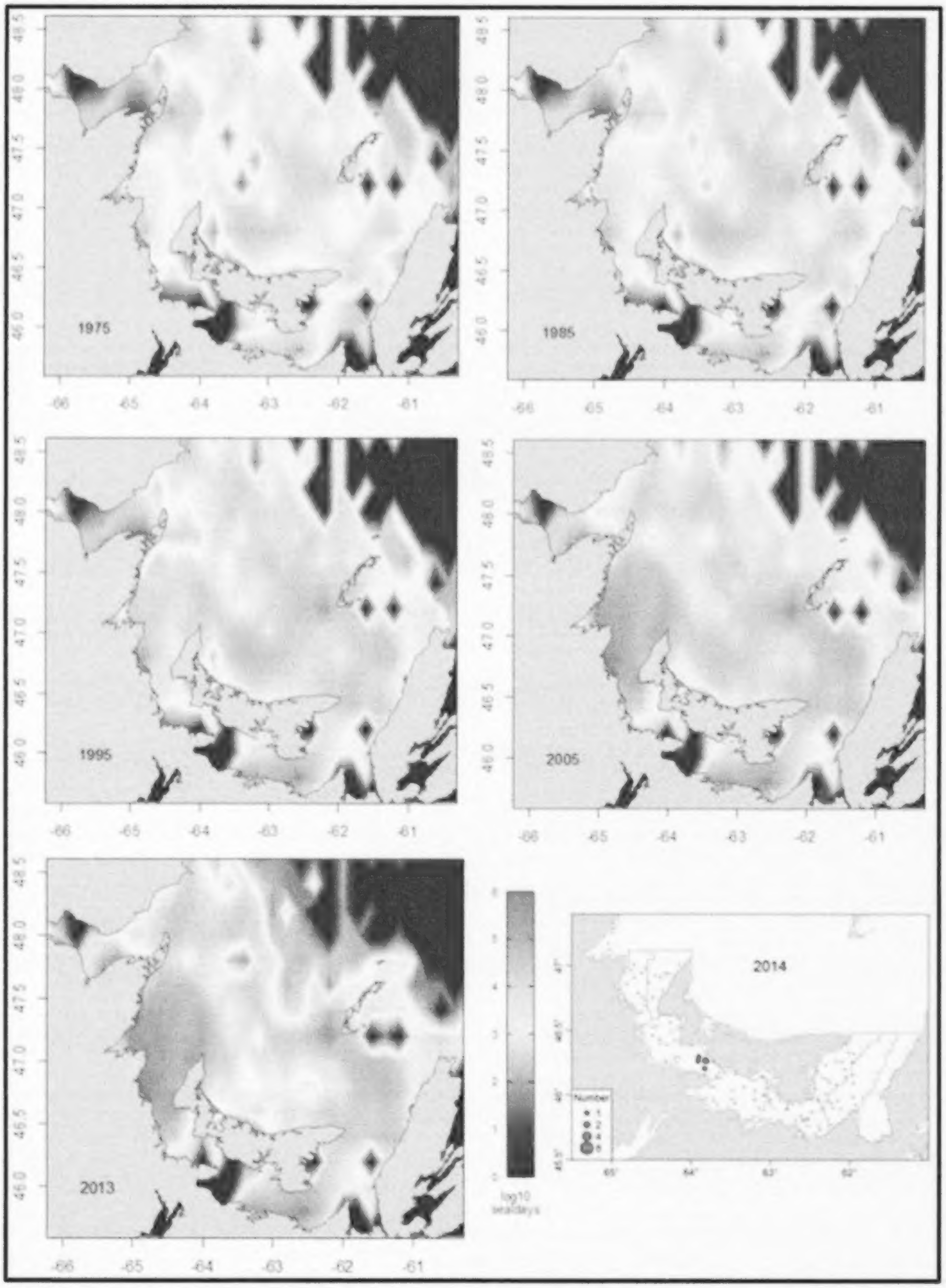
1975
1985
1995
2005
2013
2014
log10 sealdays
Number
48.5
48.0
47.5
47.0
46.5
46.0
-66
-65
-64
-63
-62
-61

*Figure 77. Inferred spatial distribution of Grey Seal in the southern Gulf of St. Lawrence, expressed as an index of the number of seal-days, for mid-point years in each of five decades (redrawn from Swain et al. 2015), and the distribution of adult Winter Skate catches in the 2014 survey bottom-trawl survey of the Northumberland Strait (lower right panel).*

# APPENDICES

## APPENDIX 1: BETWEEN-READER AGEING COMPARISON

Winter Skate were aged using thin sections of their vertebrae. Processing of vertebrae and ageing were based on the methods used by McPhie and Campana( 2009). Smaller vertebrae were sectioned and the sections mounted on glass slides. Larger vertebrae were embedded in epoxy resin and then sectioned. The entire sample of 591 sectioned vertebrae was aged by reader 1 using reflected light. The smaller vertebrae mounted on glass slides (358 vertebrae) were aged by a second reader using transmitted light.

Ages are compared between readers in Figure A1.1. The scatter of age comparisons is approximately centered on the 1:1 line. The intercept of a linear regression model predicting reader-2 age from reader-1 age (Fig. A1.1a) was not significant at the 0.05 level ($P = 0.10$). The slope of the model without an intercept (Fig. A1.1b) was near 1 (0.975, SE = 0.014), with the model accounting for 94% of the variation in ages.

While there did not appear to be much overall bias between readers, this depended on age (Fig. A1.2). Vertebrae aged as 1 year old by reader 1 were mostly aged as 0 years old by reader 2. There was little bias between readers at ages 2 to 4 years old, with the modal difference at 0 and negative and positive differences distributed approximately evenly around zero. Vertebrae aged as 5 years by reader 1 tended to be assigned a lower age by reader 2 (53% lower, 17% higher). At ages 6 and 7 based on reader 1, equal numbers of vertebrae were assigned higher and lower ages by reader 2. However, sample sizes were low for ages 1 and 5 to 8. The ages with large sample sizes (2 to 4) showed little bias between agers.

Length distributions at age were similar between readers for ages 2 to 5 comparing only the slide-mounted vertebrae (which were aged by both readers; top panel Fig. A1.3). Sample sizes were very small at the older ages in this comparison. Including the larger vertebrae aged by only reader 1, length at age remained similar between readers for ages 2 to 4, but mean lengths at age were considerably greater for ages 5 to 8 based on reader 1 ages (bottom panel Fig. A1.3). This reflected the biased subsample aged by reader 2 (i.e., only the smaller slide-mounted vertebrae).

Growth curves differed substantially between the readers, reflecting the biased subsample available to reader 2 (Fig. A1.4). Based on the entire sample of vertebrae available to reader 1, the asymptotic length ($L_\infty$) was estimated to be 77 cm. This is larger than the largest fish aged (67 cm) but larger individuals (70 to 75 cm in length) were captured in the surveys in the early to mid-1980s (Swain et al. 2006a). Based on the biased subsample available to reader 2 (omitting the large epoxy-embedded vertebrae), $L_\infty$ was estimated to be 53 cm, clearly too low.

Given the lack of large vertebrae available to reader 2, the length at age data used in this document were those based on the ages obtained by reader 1. While lengths at age 1 year differed between the two readers, length distributions were similar between readers at ages 2 to 5 years, for vertebrae read by both readers. Insufficient vertebrae at greater ages were available to reader 2 to make reliable comparisons.

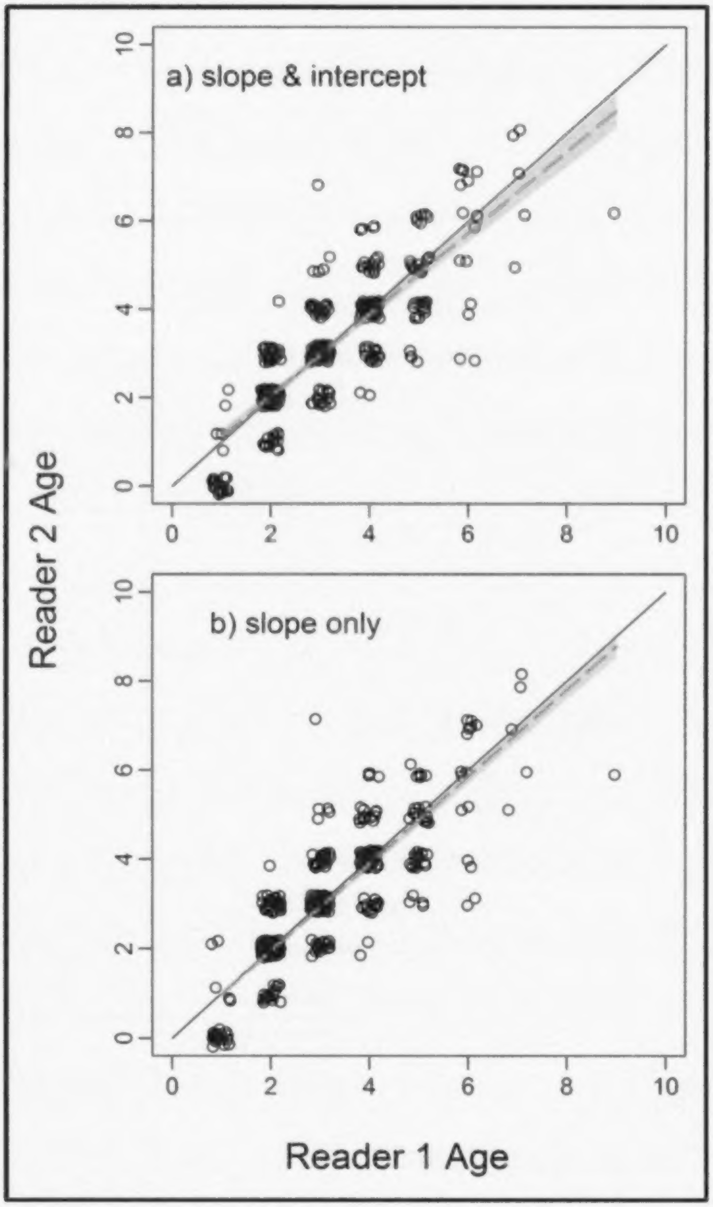

*Figure A1.1. Correspondence between ages obtained by readers 1 and 2 for Winter Skate. Points were "jittered" to reduce the superimposition of symbols by adding a small random number. The solid line is the 1:1 line. The red dashed line shows the linear regression of reader 2 ages against reader 1 ages for a model that included (panel a) or excluded (panel b) an intercept. Shading shows the 95% confidence interval around the regression line.*

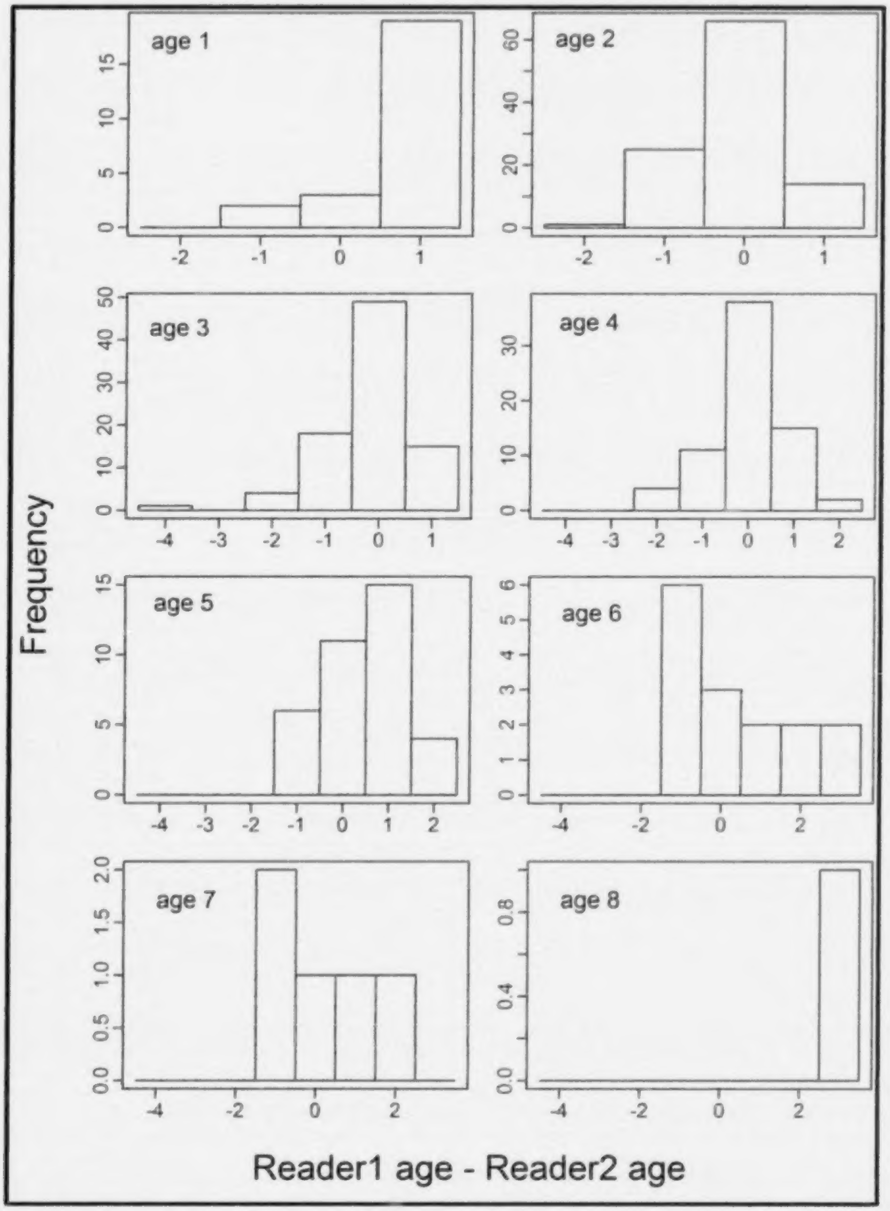

*Figure A1.2. Histogram plots of the frequencies of the differences in age interpretations of Winter Skate between readers. The difference is calculated as reader 1 age minus reader 2 age, plotted separately by age based on reader 1 age interpretation.*

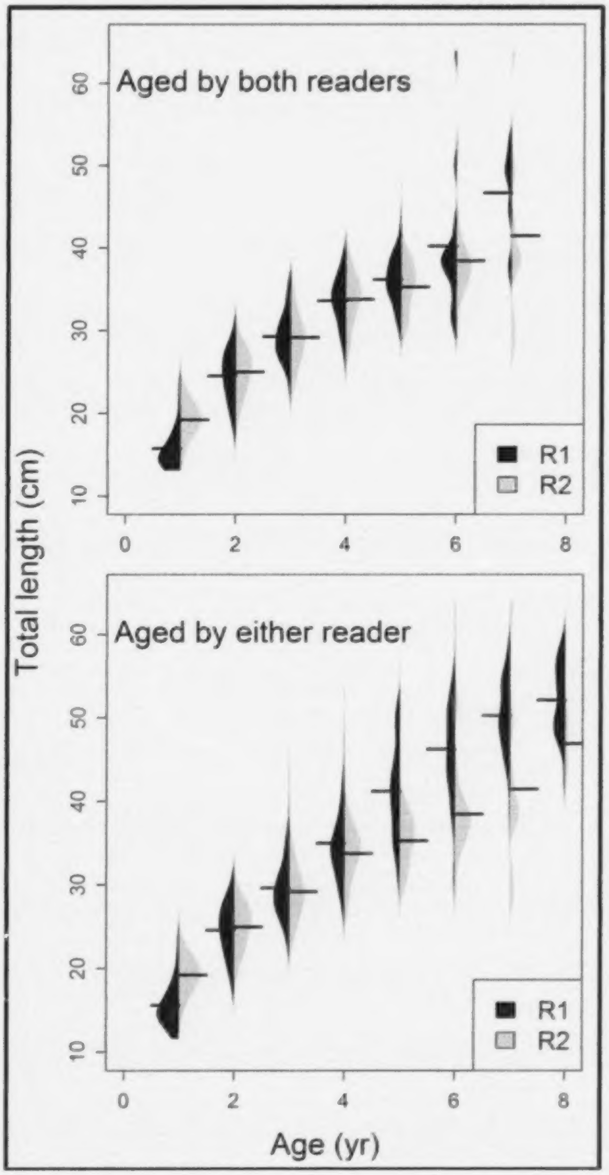

*Figure A1.3. Distributions of lengths-at-age of Winter Skate based on ages obtained by readers 1 and 2 (R1 and R2). Horizontal lines are the mean lengths at age. Only vertebrae that were read by both readers (i.e., the smaller vertebrae mounted on glass slides) were included in the top panel. The bottom panel also includes the larger epoxy-embedded vertebrae that were read by only reader 1.*

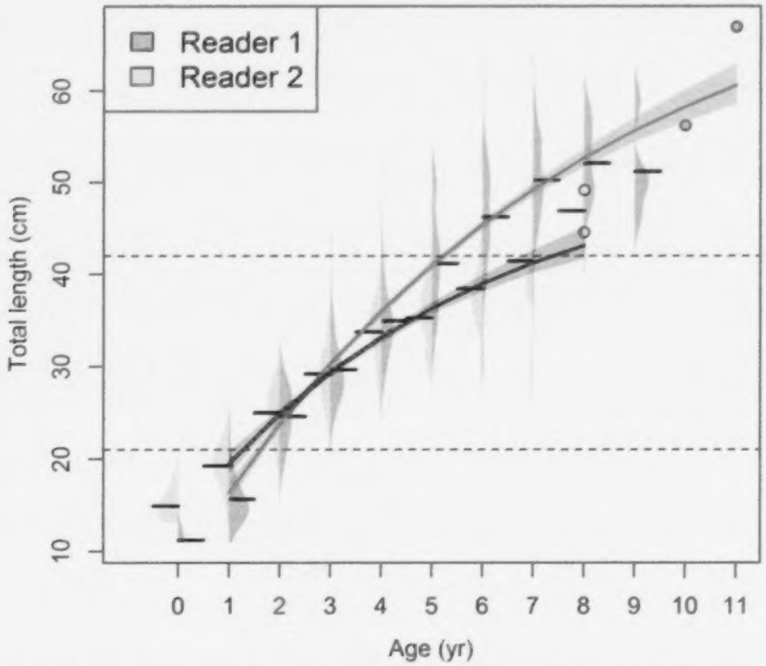

*Figure A1.4. Fit of a von Bertalanffy model to the length at age data for Winter Skate obtained by readers 1 (red shading and lines) and reader 2 (blue shading and lines). Lines show the median predicted values for each model and shading the 95% confidence intervals. Solid horizontal lines show the mean lengths at age by age and reader. Circles show individual observations. "Half beans" show the distribution of lengths at age when there are more than two observations at age.*

# APPENDIX 2: ESTIMATED WINTER SKATE LANDINGS, DISCARDS AND DISCARD MORTALITY RATES

*Table A2.1. Summary of estimated Winter Skate landings (all fisheries; in tonnes), discards (scallop fishery and groundfish and shrimp fisheries; in tonnes) and discard mortality rates (DMR). In each case LCI and UCI are respectively, the estimated lower and upper 95% confidence intervals. A fixed DMR value is assumed for the Winter Skate discards in the scallop fishery based on DFO (2010).*

| | Landings (t) | | | Discards (t) - Scallop fishery | | | | Discards (t) – Groundfish and Shrimp fisheries | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Estimate | LCI | UCI | Estimate | LCI | UCI | DMR | Estimate | LCI | UCI | DMR | LCI$_{DMR}$ | UCI$_{DMR}$ |
| 1971 | 1.26 | 0.71 | 2.09 | 178.78 | 71.22 | 378.56 | 0.1 | 599.90 | 366.50 | 919.00 | 0.35 | 0.21 | 0.54 |
| 1972 | 0.31 | 0.18 | 0.52 | 147.98 | 59.64 | 310.32 | 0.1 | 733.68 | 464.52 | 1096.11 | 0.34 | 0.18 | 0.54 |
| 1973 | 0.47 | 0.27 | 0.78 | 92.11 | 37.56 | 194.15 | 0.1 | 709.21 | 452.31 | 1048.00 | 0.35 | 0.19 | 0.55 |
| 1974 | 20.72 | 11.78 | 34.49 | 61.23 | 25.41 | 127.68 | 0.1 | 689.72 | 461.48 | 980.92 | 0.37 | 0.19 | 0.56 |
| 1975 | 20.56 | 11.69 | 34.23 | 81.74 | 33.90 | 168.19 | 0.1 | 570.83 | 372.19 | 823.97 | 0.35 | 0.20 | 0.54 |
| 1976 | 6.75 | 3.84 | 11.23 | 100.10 | 40.96 | 203.88 | 0.1 | 782.44 | 499.42 | 1175.98 | 0.32 | 0.16 | 0.53 |
| 1977 | 0.78 | 0.45 | 1.31 | 54.67 | 22.47 | 110.97 | 0.1 | 310.19 | 212.92 | 432.94 | 0.39 | 0.24 | 0.56 |
| 1978 | 1.88 | 1.07 | 3.14 | 62.33 | 25.25 | 125.93 | 0.1 | 252.21 | 167.64 | 363.83 | 0.34 | 0.20 | 0.53 |
| 1979 | 2.67 | 1.52 | 4.44 | 68.18 | 27.45 | 136.85 | 0.1 | 407.36 | 244.58 | 646.44 | 0.28 | 0.15 | 0.50 |
| 1980 | 3.45 | 1.96 | 5.75 | 65.70 | 26.46 | 130.94 | 0.1 | 325.12 | 203.06 | 496.77 | 0.27 | 0.14 | 0.48 |
| 1981 | 10.36 | 5.89 | 17.24 | 93.02 | 37.49 | 188.21 | 0.1 | 364.77 | 224.37 | 578.00 | 0.28 | 0.14 | 0.50 |
| 1982 | 0.16 | 0.09 | 0.26 | 61.09 | 24.41 | 124.84 | 0.1 | 329.62 | 204.34 | 525.16 | 0.27 | 0.14 | 0.50 |
| 1983 | 5.49 | 3.12 | 9.14 | 87.01 | 34.90 | 176.76 | 0.1 | 372.44 | 226.61 | 598.81 | 0.26 | 0.12 | 0.50 |
| 1984 | 0.00 | 0.00 | 0.00 | 61.55 | 24.85 | 124.47 | 0.1 | 106.64 | 76.05 | 146.03 | 0.34 | 0.20 | 0.51 |
| 1985 | 0.00 | 0.00 | 0.00 | 56.91 | 22.87 | 113.36 | 0.1 | 225.09 | 139.46 | 354.92 | 0.25 | 0.12 | 0.47 |
| 1986 | 0.47 | 0.27 | 0.78 | 52.37 | 21.07 | 106.22 | 0.1 | 312.94 | 181.60 | 508.47 | 0.23 | 0.11 | 0.48 |
| 1987 | 0.00 | 0.00 | 0.00 | 40.14 | 16.12 | 81.18 | 0.1 | 277.22 | 169.51 | 436.48 | 0.25 | 0.13 | 0.47 |
| 1988 | 0.16 | 0.09 | 0.26 | 37.70 | 15.17 | 77.42 | 0.1 | 239.52 | 147.56 | 380.64 | 0.25 | 0.12 | 0.49 |
| 1989 | 0.16 | 0.09 | 0.26 | 44.09 | 18.11 | 91.21 | 0.1 | 262.06 | 161.27 | 412.31 | 0.25 | 0.12 | 0.48 |
| 1990 | 0.11 | 0.06 | 0.18 | 34.43 | 13.86 | 71.04 | 0.1 | 222.42 | 149.85 | 330.76 | 0.27 | 0.12 | 0.49 |
| 1991 | 1.31 | 0.22 | 1.90 | 32.19 | 13.14 | 65.99 | 0.1 | 169.67 | 68.76 | 308.09 | 0.44 | 0.28 | 0.59 |
| 1992 | 0.56 | 0.10 | 0.78 | 27.49 | 11.28 | 56.67 | 0.1 | 311.78 | 190.00 | 513.26 | 0.17 | 0.12 | 0.22 |
| 1993 | 2.48 | 0.94 | 3.51 | 33.35 | 13.29 | 68.67 | 0.1 | 48.67 | 28.85 | 77.02 | 0.36 | 0.18 | 0.55 |
| 1994 | 1.02 | 0.16 | 13.12 | 27.82 | 11.20 | 56.16 | 0.1 | 29.98 | 15.37 | 48.99 | 0.27 | 0.14 | 0.47 |
| 1995 | 7.66 | 4.11 | 12.18 | 25.44 | 10.49 | 50.58 | 0.1 | 28.99 | 14.59 | 62.46 | 0.15 | 0.08 | 0.24 |
| 1996 | 0.84 | 0.08 | 7.42 | 24.68 | 10.41 | 47.90 | 0.1 | 18.34 | 10.47 | 26.13 | 0.25 | 0.14 | 0.39 |
| 1997 | 2.05 | 0.21 | 6.71 | 20.46 | 8.64 | 39.08 | 0.1 | 85.26 | 38.15 | 237.57 | 0.11 | 0.05 | 0.21 |
| 1998 | 0.58 | 0.06 | 3.74 | 15.91 | 6.75 | 30.19 | 0.1 | 14.07 | 9.13 | 20.96 | 0.29 | 0.19 | 0.43 |
| 1999 | 0.40 | 0.01 | 1.86 | 10.16 | 4.36 | 18.68 | 0.1 | 30.74 | 15.92 | 50.14 | 0.40 | 0.16 | 0.63 |
| 2000 | 3.42 | 0.61 | 3.75 | 8.51 | 3.71 | 15.43 | 0.1 | 29.71 | 20.41 | 41.26 | 0.26 | 0.13 | 0.41 |
| 2001 | 0.66 | 0.01 | 2.60 | 4.91 | 2.19 | 8.68 | 0.1 | 16.36 | 11.49 | 22.20 | 0.27 | 0.16 | 0.39 |
| 2002 | 1.43 | 0.03 | 3.68 | 3.01 | 1.36 | 5.21 | 0.1 | 9.75 | 6.60 | 13.39 | 0.14 | 0.08 | 0.21 |
| 2003 | 0.01 | 0.00 | 0.00 | 2.58 | 1.18 | 4.29 | 0.1 | 6.34 | 3.41 | 9.73 | 0.17 | 0.08 | 0.28 |
| 2004 | 0.32 | 0.00 | 1.45 | 2.24 | 1.05 | 3.62 | 0.1 | 7.45 | 5.34 | 10.08 | 0.15 | 0.08 | 0.24 |
| 2005 | 0.21 | 0.00 | 1.04 | 1.68 | 0.80 | 2.58 | 0.1 | 2.24 | 1.03 | 3.90 | 0.15 | 0.05 | 0.28 |

|  | Landings (t) |  |  | Discards (t) - Scallop fishery |  |  |  | Discards (t) – Groundfish and Shrimp fisheries |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Estimate | LCI | UCI | Estimate | LCI | UCI | DMR | Estimate | LCI | UCI | DMR | $LCI_{DMR}$ | $UCI_{DMR}$ |
| 2006 | 0.14 | 0.00 | 0.73 | 1.21 | 0.58 | 1.82 | 0.1 | 17.46 | 6.18 | 38.33 | 0.19 | 0.04 | 0.43 |
| 2007 | 0.04 | 0.00 | 0.52 | 1.43 | 0.68 | 2.13 | 0.1 | 6.83 | 4.23 | 9.36 | 0.05 | 0.02 | 0.13 |
| 2008 | 0.28 | 0.00 | 0.77 | 1.09 | 0.52 | 1.65 | 0.1 | 4.14 | 2.28 | 7.27 | 0.03 | 0.01 | 0.07 |
| 2009 | 1.16 | 0.00 | 3.60 | 1.16 | 0.54 | 1.80 | 0.1 | 3.46 | 1.33 | 8.00 | 0.07 | 0.01 | 0.15 |
| 2010 | 1.03 | 0.16 | 1.83 | 0.80 | 0.34 | 1.32 | 0.1 | 2.73 | 1.76 | 3.92 | 0.05 | 0.01 | 0.13 |
| 2011 | 0.34 | 0.00 | 0.88 | 0.92 | 0.36 | 1.65 | 0.1 | 3.30 | 1.73 | 5.70 | 0.03 | 0.01 | 0.06 |
| 2012 | 0.21 | 0.03 | 0.46 | 0.88 | 0.29 | 1.79 | 0.1 | 2.47 | 1.55 | 3.84 | 0.07 | 0.02 | 0.15 |
| 2013 | 0.04 | 0.00 | 0.00 | 1.02 | 0.25 | 2.35 | 0.1 | 1.63 | 1.05 | 2.34 | 0.02 | 0.00 | 0.08 |
| 2014 | 0.01 | 0.00 | 0.02 | 0.99 | 0.19 | 2.53 | 0.1 | 0.56 | 0.19 | 1.14 | 0.05 | 0.00 | 0.20 |

## APPENDIX 3: PRIORS DERIVED FROM LIFE-HISTORY DATA

A prior for $\theta$, the probability of transition from the juvenile to the adult stage, was developed based on the available growth data. Based on these data, Winter Skate enter the juvenile stage (21 cm TL) at about age 2 years of age (Fig. 1). Three years later at age 5 years, half of these fish have transitioned to the adult stage, with most of the remainder maturing at age 6 ((Fig. 1). Thus, the average time to maturation following entry to the juvenile stage is 3.5 years, yielding an annual transition probability of 0.2857 (1/3.5).

The prior for recruitment rate to the juvenile stage (age 2) was based on information on fecundity, incubation time, egg case mortality and mortality of free-swimming juveniles prior to age 2. Annual fecundity was assumed to average 30 egg cases (from Frisk et al. 2002, for Little Skate). The incubation period within egg cases was assumed to be 6 to 9 months (from Scott and Scott 1988, for Little Skate). The egg case survival rate over 6 to 9 months was assumed to average 85% (75% annually from Lucifora and Garcia 2004), and 35% was used for survival from hatching to recruitment to the juvenile stage, yielding an average recruitment rate of about 9 juveniles per female.

## APPENDIX 4: ABUNDANCE INDICES USED IN MODEL Z2

Model Z2 used abundance indices based on catch rates of juvenile (21 to 41 cm TL) and adult ($\geq$ 42 cm TL) Winter Skate in the standard RV survey strata (415 to 439) and NS survey strata 3 and 5. The adult index was constructed using the following steps:

1) Adjust the RV and NS catch rates at length for size selectivity using the Harley-Myers ogive for plaice (Harley and Myers 2001), i.e., adjusted to constant selectivity independent of length.
2) Adjust the RV and NS catch rates to the same swept area (10,000 $m^2$). Adjust the RV catch rates to the approximate catchability in the NS survey (i.e., multiply by 6).
3) Regress the log of the adjusted NS catch rate against that in the RV survey for the years when both were conducted and collected length data (2003 to 2009, 2012 to 2014). For the RV survey, use a small value (half the 2009 catch rate) for 2013 and 2014, when no adult Winter Skate was caught. The lower value in 2011 was not used because it was considered an outlier. The relationship was highly significant ($P = 0.0016$), accounting for 73% of the variation in NS catch rates (Fig. A4.1). This relationship was used to predict the mean catch rate in the NS survey in years when this information was missing (1971 to 2002, 2010 and 2011), assuming that density-dependent habitat selection by Winter Skate conformed to the predictions of the IFD.
4) Convert catch rates to trawlable abundance. Add RV trawlable abundance to observed NS trawlable abundance if available, else add to predicted NS trawlable abundance.
5) No relationship between logged juvenile catch rates in the RV and NS surveys was evident ($P = 0.52$, $R^2 = 0.053$), so a different procedure was used to construct a juvenile index accounting for juveniles in both the RV and NS survey areas. Steps 1 and 2 were the same as for the adult index. The remaining steps were:
    - For years without estimates of juvenile abundance in NS survey strata 3 and 5, total juvenile abundance (RV+NS) was obtained by multiplying RV juvenile abundance by the ratio of total juvenile biomass to RV juvenile biomass. Estimates were at the scale of trawlable abundance with all lengths adjusted to full selectivity at the approximate catchability in the NS survey. This procedure

assumes similar length distribution between RV and NS juveniles. In 2003 to 2014, the mean juvenile length was 31.8 cm in the RV survey and 30.6 cm in the NS survey. This procedure involved the following steps:

- For each year, calculate the ratio of the RV biomass index with adjustment for size selection to the biomass index without adjustment. Multiply the total biomass index without adjustment for size selection by this ratio to obtain an estimate of the total biomass index with all lengths adjusted to fully-recruited selectivity.
- Obtain estimates of total adult biomass by multiplying the RV index of adult biomass by the ratio of total adult abundance to RV adult abundance.
- Obtain an estimate of total juvenile biomass by subtracting total adult biomass from total biomass.
- Estimate the ratio of total juvenile biomass to RV juvenile biomass for each year. This ratio was calculated using smoothed time series of total and RV juvenile biomass (Fig. A4.2).

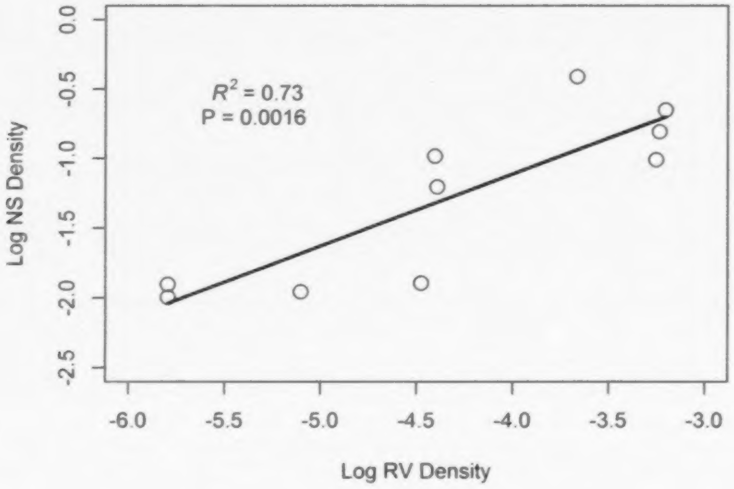

*Figure A4.1. Relationship between densities (fish per ha) of adult Winter Skate in the NS (strata 3 and 5) and RV (strata 415 to 439) surveys in 2000 to 2009 and 2012 to 2014. $R^2$ is the squared correlation coefficient, and P its significance level. Catch rates have been adjusted for size selection and differences in swept area and catchability between the RV and NS surveys.*

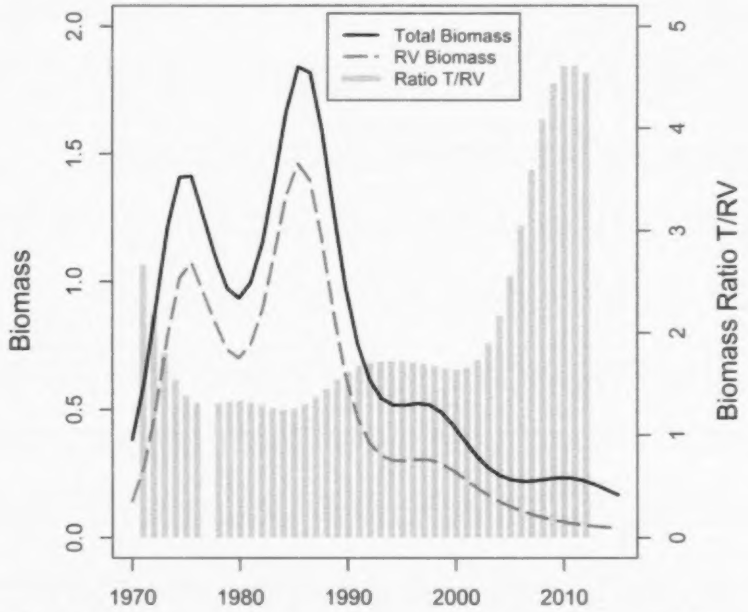

*Figure A4.2. Smoothed total and RV juvenile biomass (lines) and their ratio (bars) for Winter Skate form the southern Gulf of St. Lawrence.*

## APPENDIX 5: ESTIMATED LENGTH COMPOSITION OF FISHERY CATCHES

Size composition of the fishery catch of Winter Skate was estimated using the same methods as in the previous RPA of this DU (Swain et al. 2006a). Length frequencies of 26 commercial otter trawl catches of Thorny Skate were available from the southern Gulf in 1994 (5,494 skates measured). These were examined by mesh size (253 fish in 88 mm mesh; 2,471 fish in 161 mm mesh; 2,770 fish in 180 mm –mesh) and compared to the RV survey length frequency for 1993 to 1995. Based on these comparisons, skate retention curves were estimated for each mesh size. The mesh sizes used in the mobile gear fisheries over most of the 1971 to 2014 period were intermediate between the 88 mm and 161 mm meshes available here. Thus, a hypothetical retention curve, intermediate between those estimated for 88 mm and 161 mm meshes, was constructed. Length composition of the discarded catch was estimated for each year from 1971 to 2014 by fishing the RV survey population using the hypothetical retention curve. A 3-year running average was used for the survey length distribution. This yielded the estimated proportion of the catch in the juvenile and adult length groups in each year. The mean weight of individuals caught in the juvenile and adult length groups was estimated for each year using the survey length-weight relationships.

## APPENDIX 6: PRIOR AND POSTERIOR DISTRIBUTIONS OF PARAMETERS IN THE AGE-STRUCTURED MODEL

Life-history information for Winter Skate suggests an average recruitment rate of 9 age-2 recruits per female spawner (Appendix 3). The prior for log average recruitment rate was a normal distribution with a mean of 2.197 and a SD of 0.1. Recruitment rate deviations (on the log scale) were assumed to be normally distributed with a mean of 0 and SD of 0.2. The priors for *M* in 1971 to 1977 were normally distributed with a mean of 1.0 (juveniles) or 0.15 (adults) and SD of 0.05.

Prior distributions for abundance at age in 1971 and at age 2 in 1972 were developed as follows. First, a stable age distribution was determined with recruitment rate set at 9 recruits per female spawner, *M* equal to 0.2 for adults and 1.2 for juveniles, and no fishing mortality. Given the resulting proportions at age in the population, proportions at age in the survey catches were calculated using the selectivity at age to the survey obtained in preliminary model runs with more ad hoc prior distributions for initial abundance. Given these proportions, average abundance indices at age were calculated for the 1971 to 1975 period (based on the average total abundance index in this period). The proportions of juveniles and adults were calculated (pj1 and pa1, respectively), as were the average proportions observed in 1971 to 1975 (pj2 and pa2, respectively for juveniles and adults). Population abundance at age was then calculated using the calculated average abundance indices at age, the survey selectivity at age used above and a fully recruited catchability of 0.7 (the value estimated in the surplus production model). These population abundances were then adjusted by pj1/pj2 and pa1/pa2 to match the ratio of juveniles to adults observed in the survey in 1971 to 1975 (after accounting for selectivity at age). Priors were lognormal with these means and SD of 0.25.

The prior for fully recruited survey catchability was set at 0.7 (based on the posterior distributions from preliminary models). This prior was assumed to be normally distributed on the log scale with SD = 0.1. Priors for discard mortality in scallop and groundfish fisheries were set at 0.1 and 0.23 respectively. Prior distributions were assumed to be normally distributed on the log scale with means of -2.302585 and -1.46968 and SDs of 0.4 and 0.35, respectively. Prior and posterior distributions are shown in Figures A6.1 and A6.2.

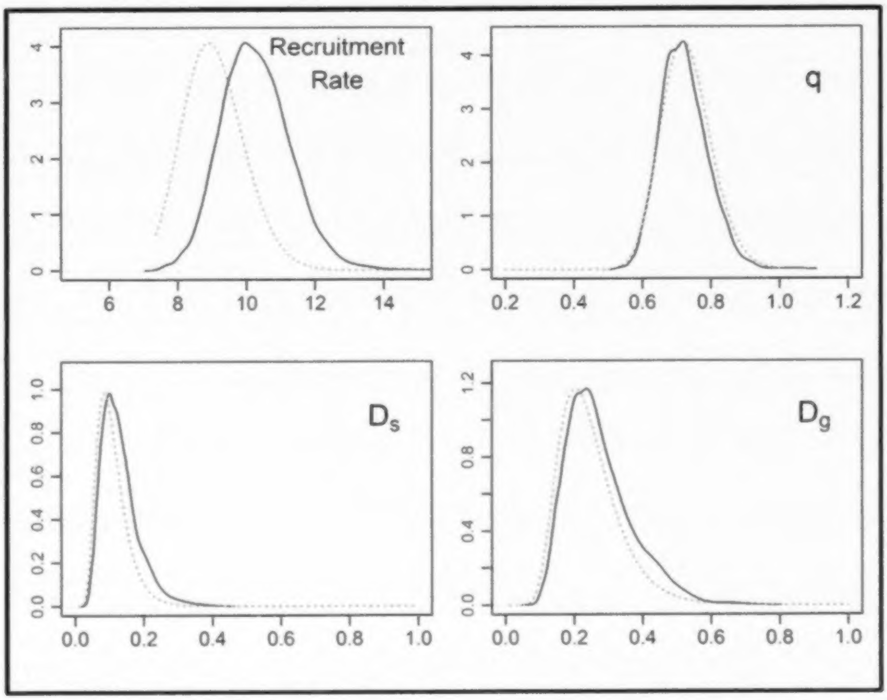

*Figure A6.1. Prior (dashed red line) and posterior distributions (solid black line) for the recruitment rate, q (fully recruited catchability to the survey), Ds (discard mortality in the scallop fishery), and Dg (mean discard mortality in groundfish fisheries) parameters in the base age-structured model of Winter Skate from the southern Gulf of St. Lawrence.*

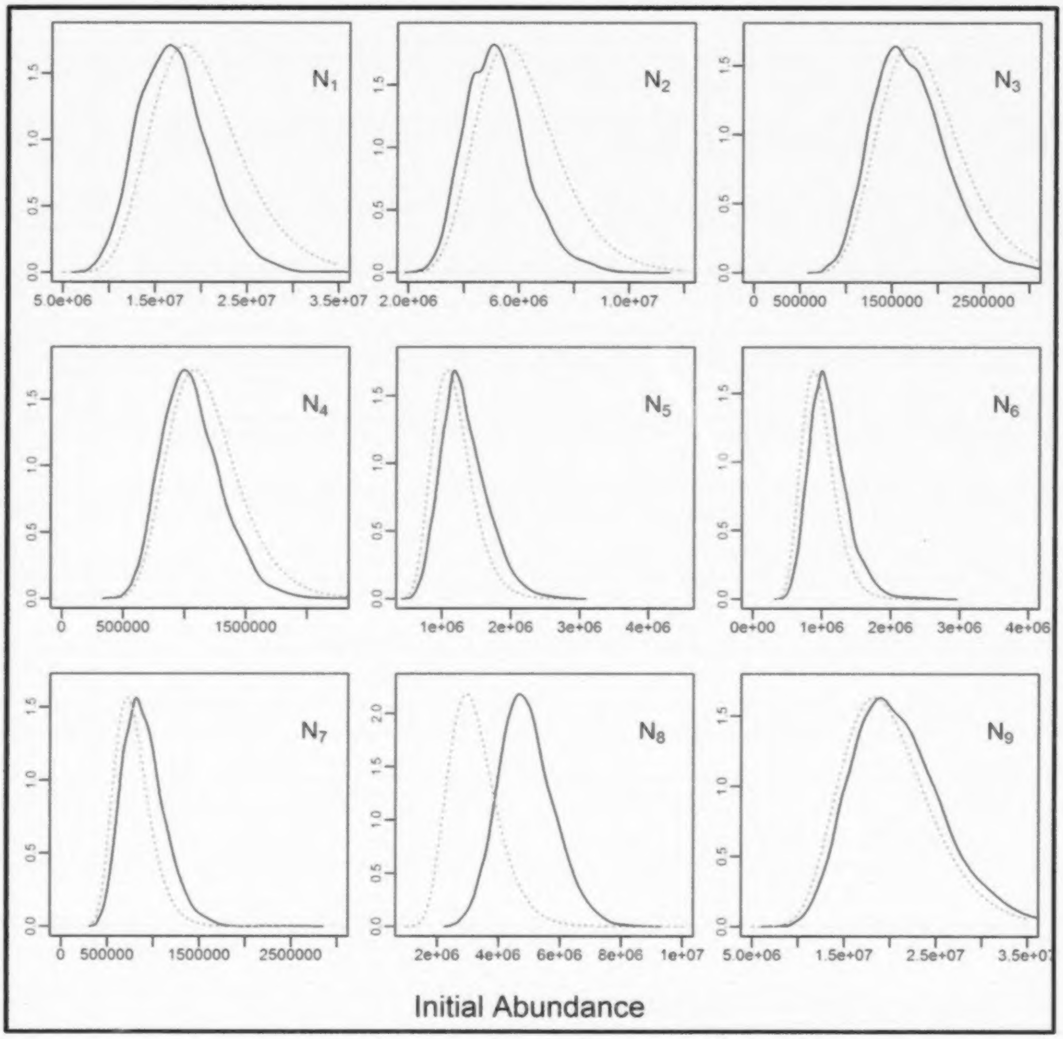

*Figure A6.2. Prior (dashed red line) and posterior distributions (solid black line) for the abundances at ages 2 to 9+ in 1971 (panels labelled $N_1$-$N_8$) and at age 2 in 1972 (panel labelled $N_9$) for Winter Skate from the southern Gulf of St. Lawrence.*

## APPENDIX 7: EFFECTS OF PRIORS FOR SURVEY Q AND STARTING ABUNDANCES AT AGE ON RESULTS OF THE AGE-STRUCTURED MODEL

The model examined here differed from the base model in two respects: the prior for survey catchability (*q*), and the priors for starting abundances at age in 1971 and at age 2 in 1972. The prior for *q* had a mean of 0.6 (compared to 0.725 in the base model). In order to obtain the priors for starting abundance at age in this model, the average 1971 to 1975 survey catch at length was first scaled to "rockhopper" catchability (by multiplying by 6) and then divided by 0.7 to scale to assumed full catchability. The age-length key (Fig. 1) was then applied to the length distribution to obtain abundances at age for the priors.

The posterior for *q* shifted from the prior to a mean value of 0.736 (Fig. A7.1), similar to the posterior in the base model (Fig. A6.1). In contrast to the base model (Fig. A6.1), the posterior for mean recruitment rate did not shift to a higher value (Fig. A7.1). The posterior distributions for starting abundances at age shifted from their priors to varying degrees in both this model (Fig. A7.2) and the base model (Fig. A6.2). Estimated abundances at age 2 in 1971 and 1972 were over an order of magnitude lower in this model than in the base model, but estimated starting abundances at older ages were more similar between models. Fits to the survey data were similar between models (Fig. 42 and A7.3), except the base model fit early adult abundance indices slightly better.

The main difference between models is that abundance early in the time series is estimated to be higher by the base model (Fig. 46) than by this model (Fig. A7.4). Juvenile abundance in the mid-1970s is estimated to be about 40 million by this model and 70 million by the base model. Adult abundance in 1971 is estimated to be 6 million by this model and 8 million by the base model. However, both models indicate severe and ongoing declines in both juvenile and adult abundance. Juvenile abundance in 2014 was estimated to be 3% and 5% of the 1971 to 1989 average by the base model and this model, respectively. Similarly, adult abundances in 2014 were estimated to be 2% and 3% of the 1971 to 1979 average abundances for the base model and this model, respectively. A peculiar feature of the estimated juvenile abundance by this model is a sudden sharp increase in abundance between 1972 and 1973. Abundance at age 2 is first estimated by the model using recruitment rate and adult abundance in 1973. The sharp increase in age-2 abundance when this first occurs suggests that the priors for age-2 abundance in 1971 and 1972 may have been too low in this model.

Both models indicate that declining abundance is due to large increases in adult *M* (Figs. 48 and A7.5). Estimated juvenile *M* is similar between models, with no large changes over time (Figs. 48 and A7.5). No trends in recruitment rate are evident in both cases (Figs. 47 and A7.6). Estimated *F* is at similar, very low levels in both cases (Figs. 49 and A7.7).

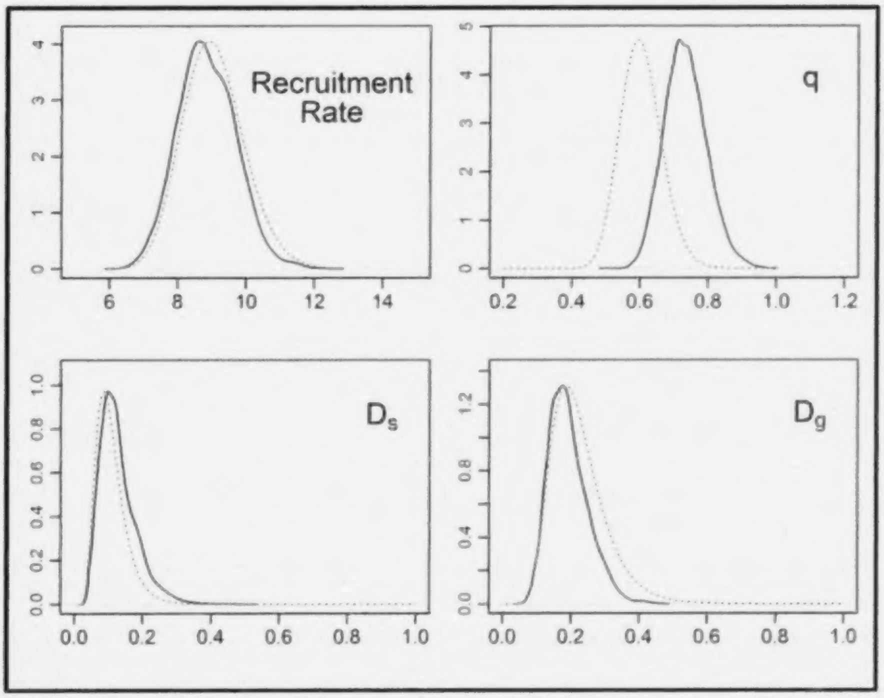

*Figure A7.1. Prior (dashed red line) and posterior distributions (solid black line) for the recruitment rate, q (fully recruited catchability to the survey), Ds (discard mortality in the scallop fishery), and Dg (mean discard mortality in groundfish fisheries) parameters in the alternate age-structured model for Winter Skate from the southern Gulf of St. Lawrence.*

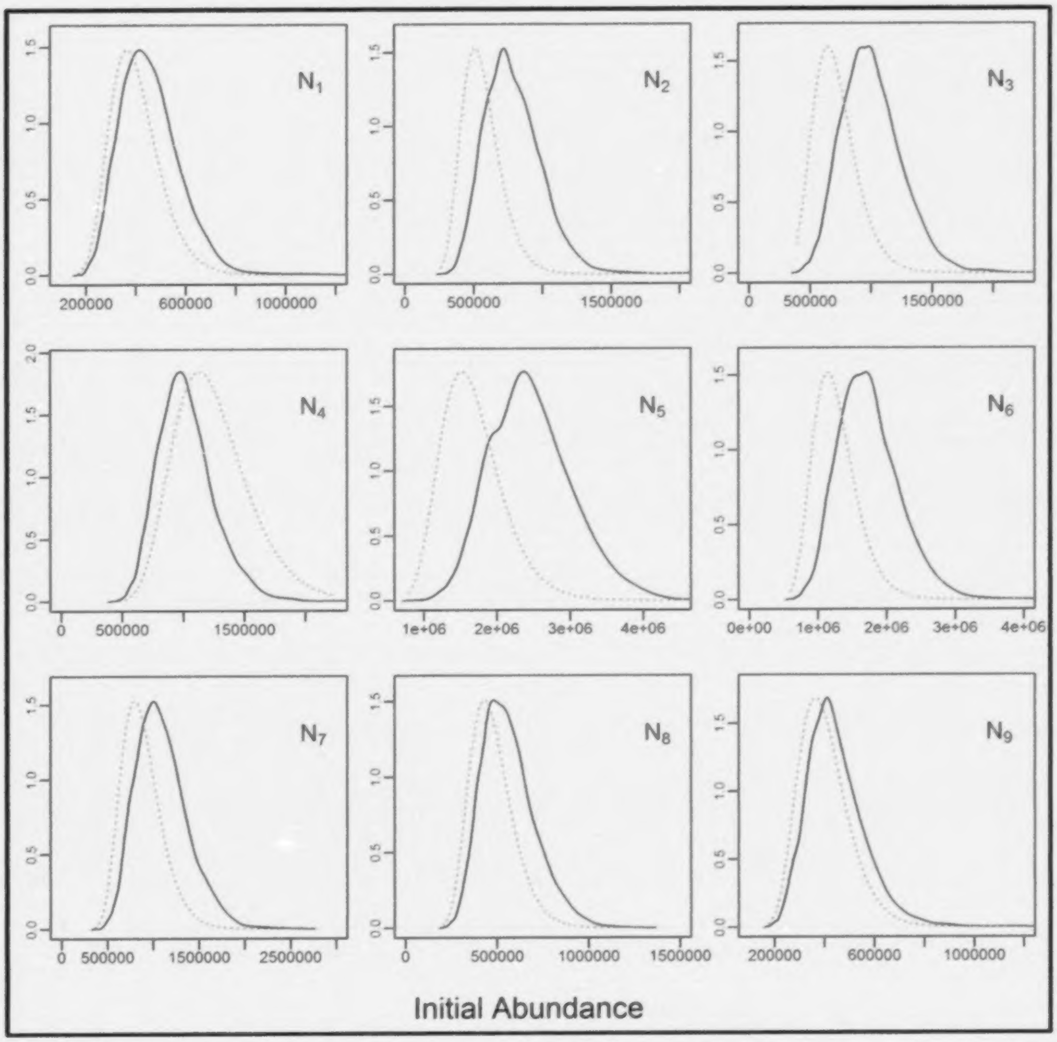

*Figure A7.2. Prior (dashed red line) and posterior distributions (solid black line) for the abundances at ages 2 to 9+ in 1971 (panels labelled $N_1$-$N_8$) and at age 2 in 1972 (panel labelled $N_9$) from the alternate model for Winter Skate from the southern Gulf of St. Lawrence.*

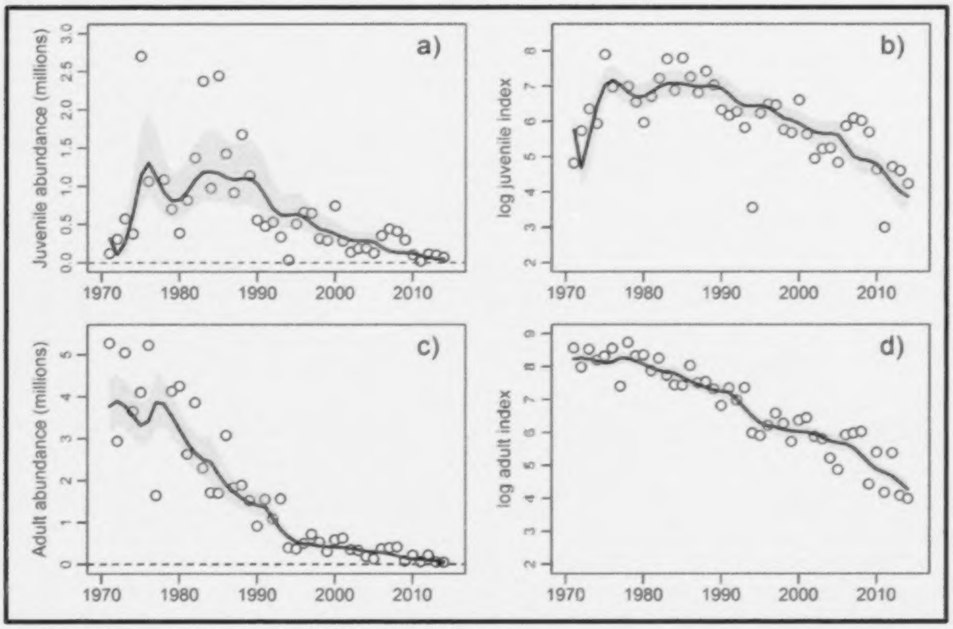

*Figure A7.3. Fit of the alternate age-structured model to the juvenile (21 to 41 cm; panels a and b) and adult (≥42 cm; panels c and d) Winter Skate abundance (millions) indices on the arithmetic (panels a and c) and log (panels b and d) scales. Circles are the observed indices and lines and shading show the median and 95% confidence intervals of the predicted values.*

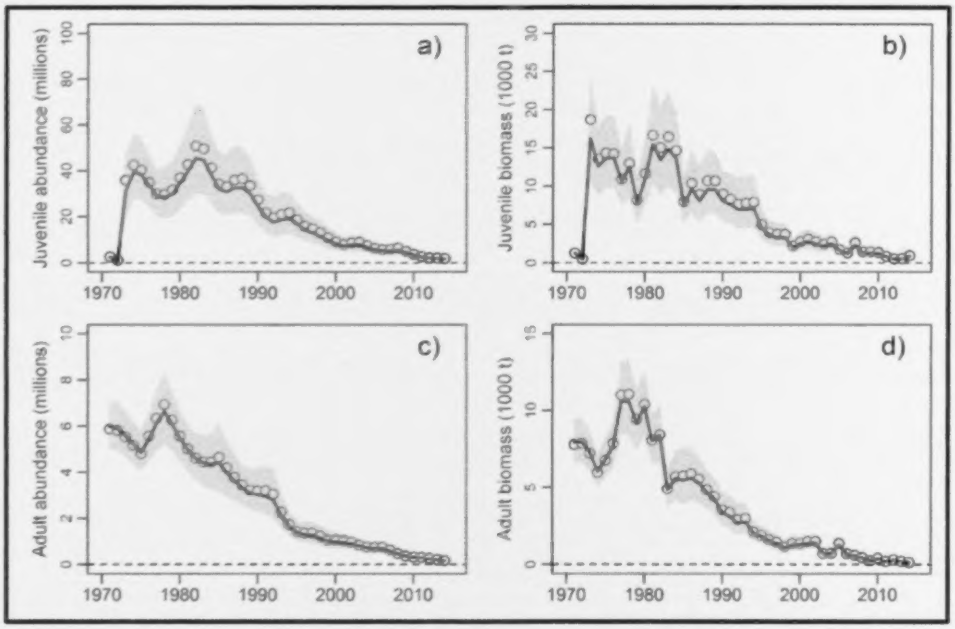

*Figure A7.4. Estimated abundances (millions; panels a and c) and biomass (1000 t; panels b and d) of juvenile (panels a and b) and adult (panels c and d) Winter Skate in the southern Gulf of St. Lawrence, based on the alternate age-structured model. Lines and shading show the median and 95% confidence intervals of the estimated values based on MCMC sampling. Circles show the maximum likelihood estimates.*

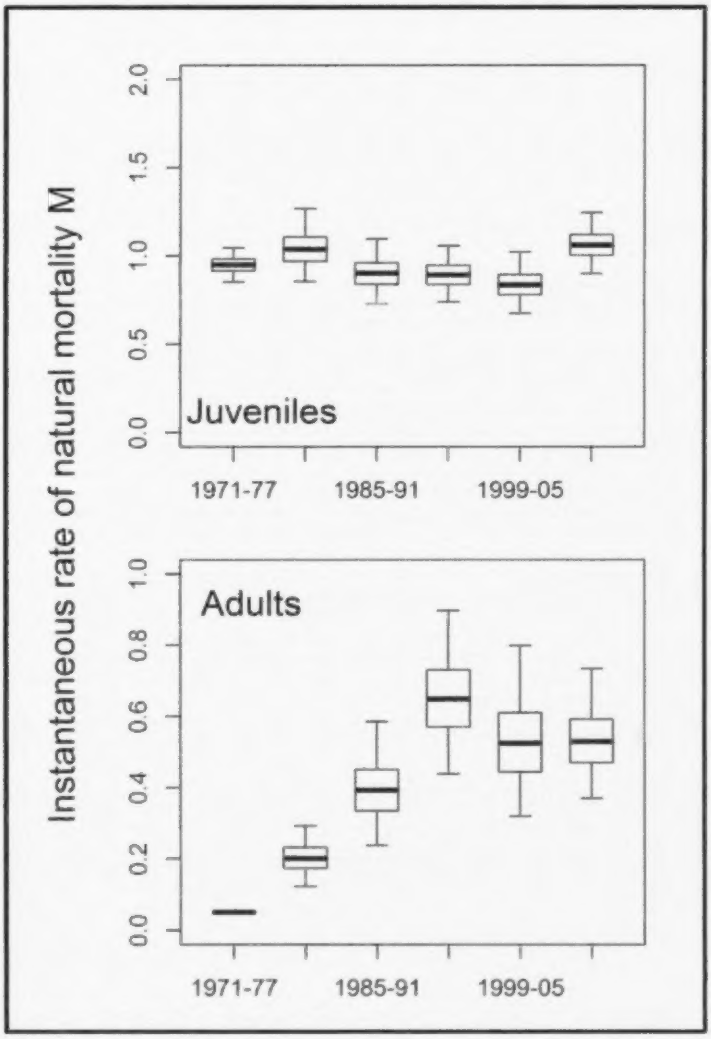

*Figure A7.5. Estimated instantaneous rates of natural mortality (M) of juvenile (age 2-4 years; upper panel) and adult (aged 6+ years; lower panel) Winter Skate from the southern Gulf of St. Lawrence, by time period, estimated by the alternate age-structured model. Horizontal lines are the median estimates, boxes the 25th to 75th percentiles and vertical lines the 95% confidence intervals. M of 5 year olds was assumed to be the average of the M values at younger and older ages.*

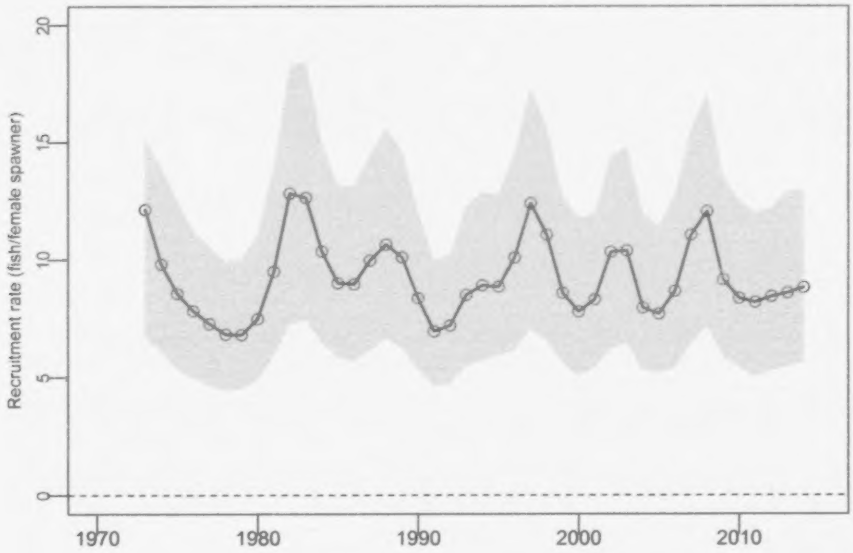

*Figure A7.6. Estimated recruitment rates at age 2 by cohort of Winter Skate in the southern Gulf of St. Lawrence, by year of recruitment at age 2. The median estimates are indicated by the line and their 95% confidence intervals by the shading. Estimates are based on the alternate age-structured model.*

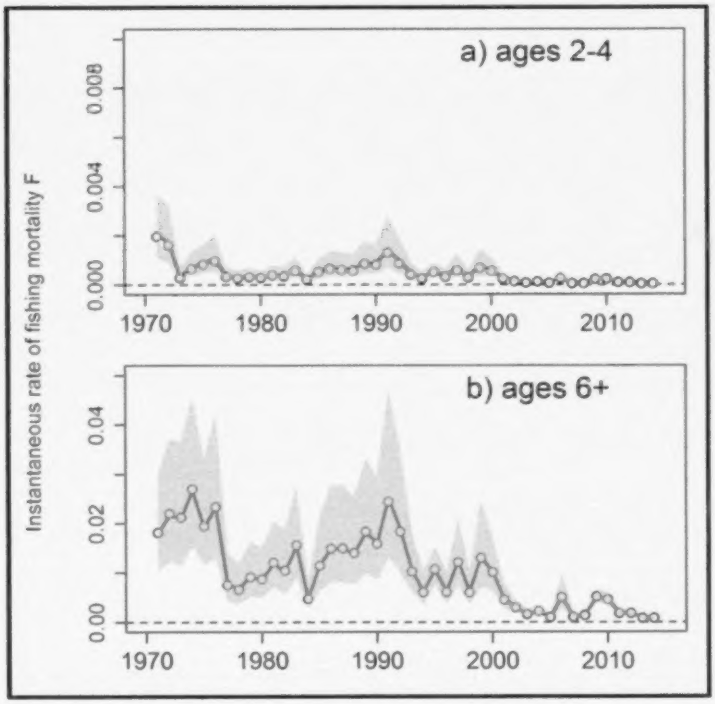

*Figure A7.7. Estimates of the instantaneous rates of fishing mortality (F) for juvenile (aged 2 to 4 years) and adult (6 years and older; lower panel) Winter Skate from the southern Gulf of St. Lawrence. Lines and circles show the median estimates and shading their 95% confidence intervals. Estimates are based on the alternate age-structured model.*